

Empirical modelling of the BLASTPol achromatic half-wave plate for precision submillimetre polarimetry

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ABSTRACT

A cryogenic achromatic half-wave plate (HWP) for submillimetre astronomical polarimetry has been designed, manufactured, tested, and deployed in the Balloon-borne Large-Aperture Submillimeter Telescope for Polarimetry (BLASTPol). The design is based on the five-slab Pancharatnam recipe and it works in the wavelength range 200–600 μm , making it the most achromatic HWP built to date at submillimetre wavelengths. The frequency behaviour of the HWP has been fully characterised at room and cryogenic temperatures with incoherent radiation from a polarising Fourier transform spectrometer. We develop a novel empirical model, complementary to the physical and analytical ones available in the literature, that allows us to recover the HWP Mueller matrix and phase shift as a function of frequency and extrapolated to 4 K. We show that most of the HWP non-idealities can be modelled by quantifying one wavelength-dependent parameter, the position of the HWP equivalent axes, which is then readily implemented in a map-making algorithm. We derive this parameter for a range of spectral signatures of input astronomical sources relevant to BLASTPol, and provide a benchmark example of how our method can yield unprecedented accuracy on measurements of the polarisation angle on the sky at submillimetre wavelengths.

Key words: instrumentation: polarimeters — techniques: polarimetric — balloons — magnetic fields — polarisation — submillimetre.

1 INTRODUCTION

Star formation occurs in the cold interstellar medium (ISM) where the gas is mostly found in molecular form. A small fraction, typically 10^{-6} , of gas particles ionised by cosmic rays provides strong coupling between the cold gas and the

ambient interstellar magnetic field. Thus magnetic fields might play a crucial role in the evolution of star-forming clouds, perhaps controlling the rate at which stars form and even determining the masses of stars (see review articles by Crutcher 2004; McKee & Ostriker 2007). Although the importance of magnetic fields was suggested as early as 1956 by Mestel & Spitzer, it has not yet been possible to clearly establish their influence on Giant Molecular Clouds

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(GMCs) and star formation. This lack of understanding is caused by the difficulty in observing Galactic magnetic fields on the spatial scales relevant to the star-forming processes, especially within obscured molecular clouds (see e.g., Crutcher et al. 2004; Whittet et al. 2008).

The only direct method for determining the strength of the magnetic field is to measure the splitting of molecular lines through the Zeeman effect (e.g., Crutcher 1999). This has been carried out successfully for a number of molecular cloud cores, though the technique is difficult and is limited to the brightest of regions (Crutcher et al. 1999). In addition, this method only yields the component of the magnetic field along the line of sight, and so can only be used to determine the average field strength for a statistical sample of cores.

One promising alternative method for probing Galactic magnetic fields is to observe clouds with a far-infrared/submillimetre (FIR/submm) polarimeter (e.g., Hildebrand et al. 2000; Ward-Thompson et al. 2000). By tracing the linearly polarised thermal emission from dust grains aligned with respect to the local magnetic fields, we can estimate the direction of the plane-of-the-sky component of the field within the cloud (see e.g., Lazarian 2007), and its strength via the Chandrasekhar & Fermi (CF; 1953) technique, provided that ancillary measurements of the turbulent motion velocity are available.

Ground-based observations with the SCUBA polarimeter (Murray et al. 1997; Greaves et al. 2003) and the Submillimetre Polarimeter for Antarctic Remote Observations (SPARO; Novak et al. 2003) show that the submm emission from prestellar cores and GMCs is indeed polarised to a few percent (Ward-Thompson et al. 2000; Li et al. 2006). *Planck* (Ade et al. 2011) will provide coarse resolution (FWHM $\sim 5'$) submm polarimetry maps of the entire Galaxy. The Atacama Large Millimeter/submillimeter Array (ALMA; Wootten & Thompson 2009) will provide sub-arcsecond resolution millimetre (mm) and submm polarimetry, capable of resolving fields within cores and circumstellar disks, but will not be sensitive to cloud-scale fields.

The Balloon-borne Large-Aperture Submillimeter Telescope for Polarimetry (BLASTPol; Marsden et al. 2008; Fissel et al. 2010; Pascale et al. 2012), with its arcminute resolution, is the first submm polarimeter to map the large-scale magnetic fields within molecular clouds with high sensitivity and mapping speed, and sufficient angular resolution to observe into the dense cores (~ 0.1 pc). BLASTPol mapped the polarised dust emission over a wide range of column densities corresponding to $A_V \gtrsim 4$ mag, yielding hundreds to thousands of independent polarisation pseudo-vectors per cloud, for a dozen clouds. Moreover, the polarimetric observations of BLASTPol at 250, 350, and 500 μ m complement those planned for SCUBA-2 (Bastien et al. 2005; Holland et al. 2006) at 850 μ m, as BLASTPol's smaller pixel count is almost completely compensated by the increasing flux density at shorter wavelengths. In particular, BLASTPol has better sensitivity to degree-scale polarised emission. Core maps to be obtained using SCUBA-2 can be combined with those produced by BLASTPol to trace magnetic structures in the cold ISM from scales of 0.01 pc out to 5 pc, thus providing a much needed bridge between the large-area but coarse-resolution polarimetry provided by *Planck* and the high-resolution but limited field-of-view maps of ALMA.

In January 2011, BLASTPol successfully completed its first 9.5-day flight over Antarctica. Ten science targets were mapped with unprecedented combined mapping speed and resolution. BLASTPol is scheduled to fly again in December 2012 with the same apparatus to observe more targets and improve the statistics on GMCs and dark clouds. These observations will constitute an exciting dataset for studying the role played by magnetic fields in star formation.

The BLASTPol linear polarisation modulation scheme comprises a stepped cryogenic achromatic half-wave plate (HWP) and photolithographed polarising grids placed in front of the detector arrays, acting as analysers. The grids are patterned to alternate the polarisation angle sampled by 90° from bolometer-to-bolometer along the scan direction. BLASTPol scans so that a source on the sky passes along a row of detectors, and thus the time required to measure one Stokes parameter (either Q or U) is just equal to the separation between bolometers divided by the scan speed. During operations, we carry out spatial scans at four HWP rotation angles spanning 90° (22.5° steps), allowing us to measure the other Stokes parameter through polarisation rotation.

The use of a continuously rotating or stepped HWP as a polarisation modulator is a widespread technique at mm and submm wavelengths (e.g., Renbarger et al. 2004; Hanany et al. 2005; Pisano et al. 2006; Savini et al. 2006, 2009; Johnson et al. 2007; Li et al. 2008; Matsumura et al. 2009; Bryan et al. 2010b; Dowell et al. 2010). A thorough account of the HWP non-idealities and its inherent polarisation systematics, especially for very achromatic designs, has become necessary as the accuracy and sensitivity of mm/submm instruments have soared in recent years.

The literature offers numerous efforts to address, through simulations, the impact of the inevitable instrumental systematic errors due to the polarisation modulation strategy in the unbiased recovery of the Stokes parameters Q, U on the sky, especially for Cosmic Microwave Background (CMB) polarisation experiments (e.g., O'Dea et al. 2007, 2011; Brown et al. 2009). In addition, physical and analytical models have been developed to retrieve the frequency-dependent modulation function of achromatic HWPs and estimate the corrections due to non-flat source spectral indices (Savini et al. 2006, 2009; Matsumura et al. 2009).

Nevertheless, little work has been published on incorporating the *measured* HWP non-idealities in a data-analysis pipeline and ultimately in a map-making algorithm. Bryan et al. (2010b) derive an analytic model that parametrises the frequency-dependent non-idealities of a monochromatic HWP and present a map-making algorithm that convincingly accounts for these. Bao et al. (2012) carefully simulate the impact of the spectral dependence of the polarisation modulation induced by an achromatic HWP on measurements of the CMB polarisation in the presence of astrophysical foregrounds, such as Galactic dust. However, both these works assume the nominal design values for the build parameters of the HWP plus anti-reflection coating (ARC) assembly.

While this assumption is a reasonable one when no spectral measurements of the HWP as-built are available, several studies clearly show that the complex multi-slab crystal HWP and its typically multi-layer ARC are practically impossible to manufacture *exactly* to the desired specifications.

In particular, Savini et al. (2006, 2009) and Pisano et al. (2006) caution against the finite precision to which the multiple crystal substrates composing an achromatic HWP can be aligned relative to each other in the Pancharatnam (1955) scheme. In addition, Zhang et al. (2009) show how some of the design parameters in the ARC can slightly change during the bonding of layers, achieved via a hot-pressing technique (Ade et al. 2006).

This work describes a novel empirical method that allows the reconstruction of the Mueller matrix¹ of a generic HWP as a function of frequency through spectral transmission measurements of the HWP rotated by different angles with respect to the input polarised light. Not only does this method give complete and quantitative information on the *measured* spectral performance of the HWP, but it also provides a direct avenue to accounting for the non-idealities of the HWP *as-built* in a map-making algorithm. This empirical approach is applied to the BLASTPol HWP and will ultimately yield unprecedented accuracy on astronomical measurements of polarisation angles at submm wavelengths.

The layout of this paper is as follows. In Section 2, we give an overview of the manufacturing process for BLASTPol’s five-slab sapphire HWP. Section 3 describes the spectral measurements, while Section 4 presents the empirical model as well as the main results of the paper. Finally, in Section 5, we describe the algorithm for the naive-binning map-making technique implemented by BLASTPol, which naturally accounts for the *measured* HWP non-idealities. Section 6 contains our conclusions.

2 THE BLASTPol HALF-WAVE PLATE

Wave plates (or retarders) are optical elements used to change the polarisation state of an incident wave, by inducing a predetermined phase difference between two perpendicular polarisation components. A (monochromatic) wave plate can be simply obtained with a single slab of uniaxial birefringent crystal of specific thickness, which depends upon the wavelength and the index of refraction of the crystal. A birefringent crystal is characterised by four parameters, n_e , n_o , α_e , α_o , the real part of the indices of refraction and the absorption coefficient (in cm^{-1}) for the extraordinary and ordinary axes of the crystal. At a specific wavelength λ_0 , the phase shift induced by a slab is determined uniquely by its thickness d , and reads:

$$\Delta\varphi(\lambda_0) = \frac{2\pi d}{\lambda_0} (n_e - n_o) . \quad (1)$$

Given the operating wavelength λ_0 , the required phase shift for the wave plate is achieved by tuning the thickness d .

While monochromatic wave plates have been (and are still being) used in mm and submm astronomical polarimeters (see e.g., Renbarger et al. 2004; Li et al. 2008; Bryan et al. 2010a,b; Dowell et al. 2010), the inherent dependence of the phase shift on wavelength, expressed in

Equation 1, constitutes an intrinsic limit in designing a polarisation modulator that operates in a broad spectral range (i.e., is achromatic).

2.1 Achromatic half-wave plate design

Achromaticity is necessary for wave plates that are designed for use with multi-band bolometric receivers, such as BLASTPol, PILOT (Bernard et al. 2007), or SCUBA-2 (Bastien et al. 2005; Savini et al. 2009). To achieve a broad-band performance, multiple-slab solutions have been conceived in the past (Pancharatnam 1955; Title & Rosenberg 1981) to compensate and keep the phase shift approximately constant across the bandwidth, by stacking an odd number (usually 3 or 5) of birefringent substrates of the same material, which are rotated with respect to each other about their optical² axes by a frequency-dependent set of angles.

Achromatic wave plates have been designed and built for astronomical polarimeters at mm and submm wavelengths by many authors in the last decade (Hanany et al. 2005; Pisano et al. 2006; Savini et al. 2006, 2009; Matsumura et al. 2009), following the Poincaré sphere (PS) method first introduced by Pancharatnam (1955), which we briefly recall here for completeness. The polarisation state of a monochromatic wave in a given reference frame can be represented by a set of coordinates, latitude and longitude, on the PS that quantify, respectively, the ellipticity angle ($\sin 2\chi \propto \sin \Delta\varphi$) and the orientation angle of its major axis ($\tan 2\psi \propto \cos \Delta\varphi$). A linearly polarised state appears only on the equator (with $\pm Q$ and $\pm U$ at the four antipodes), while the left and right circularly polarised states ($\pm V$) lie at the north and south poles, respectively.

Propagation of a wave through a single birefringent slab will rotate its polarisation state on the PS by an amount dependent on the relation between wavelength and thickness (Equation 1), about an axis whose orientation depends upon the position of the optic axis of the wave plate with respect to the reference frame of the incoming polarisation state. Specifically, an ideal monochromatic half-wave plate produces one PS rotation of 180° , changing a linear polarisation state to another one on the equator.

When a polychromatic wave packet enters a multiple-slab HWP, the input polarised states of all wavelengths overlap in a single point on the PS. After the rotation due to the first slab, the polarisation states of different wavelengths will be scattered along an arc on the PS, with separations that depend on the bandwidth $\Delta\lambda$ of the wave packet. As anticipated, this effect can be compensated for by stacking together an odd number of birefringent slabs, rotated with respect to each other by a symmetric pattern of angles (α , β , γ , β , and α for 5 slabs) about their optical axes (as derived by e.g., Pancharatnam 1955 and Title & Rosenberg 1981). The various polarisation states regroup in a small area of the PS surface, thus achieving a nearly frequency-independent output polarisation state, within a certain $\Delta\lambda$.

¹ We adopt the Stokes (1852) formalism to represent the time-averaged polarisation state of electromagnetic radiation; for a review of polarisation basics we refer the reader to Collett (1993).

² We distinguish between “optic” axis of a crystal, i.e. the direction in which a ray of transmitted light experiences no birefringence, and “optical” axis, i.e. the imaginary line along which there is some degree of rotational symmetry in the optical system.

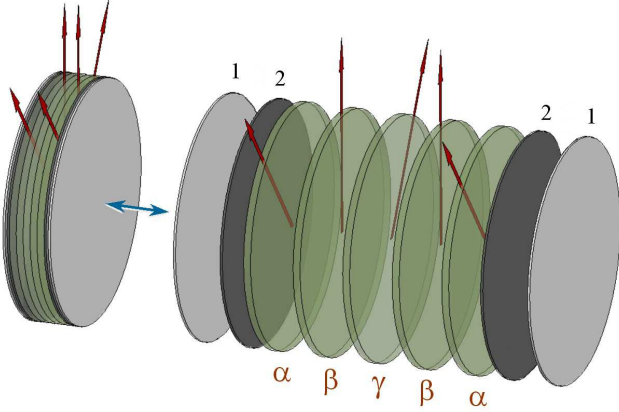


Figure 1. Exploded view of the BLASTPol HWP. We also show the two-layer anti-reflection coating described in Section 2.2.

We note that, strictly speaking, all the four parameters that characterise a crystal, n_e , n_o , α_e , α_o , depend upon wavelength (as we will illustrate in detail for sapphire); in particular, the different frequency-dependence of the ordinary and extraordinary refractive indices enters Equation 1 in a non-trivial way, thus rendering the design of an achromatic HWP increasingly difficult as $\Delta\lambda$ broadens.

Using the above PS method, we have designed a HWP for the BLASTPol instrument, which requires an extended frequency range to cover three adjacent 30% wide spectral bands at 250, 350, and 500 μm . A Pancharatnam (1955) five-slab design is chosen with axis orientations of $\alpha = 0^\circ$, $\beta = 26^\circ$, $\gamma = 90.3^\circ$, $\beta = 26^\circ$, and $\alpha = 0^\circ$; these angles are optimised using the physical and analytical model developed by Savini et al. (2006) for an achromatic HWP, which in turn is based on the work of Kennaugh & Adachi (1960). In Fig. 1 we show an exploded view of the BLASTPol HWP assembly; to our knowledge, with its $\sim 100\%$ bandwidth, this is the most achromatic half-wave plate manufactured to date at submm wavelengths³.

2.2 HWP manufacture

In addition to the broad spectral range of operation, the BLASTPol HWP is required to function at cryogenic temperatures (4 K; see Fissel et al. 2010) for two main reasons: (1) reduce the thermal emission from a warm element placed in the optical path, which would constitute a significant background load on the bolometers; and (2) reduce the losses in transmission due to absorption from the stack of five crystal substrates, which drops dramatically with temperature. The absorption in a crystal at FIR wavelengths is the result of the interactive coupling between the incident radiation and phonons – the thermally induced vibrations of the constituent atoms of the substrate crystal lattice. Because the

phonon population is much reduced at low temperatures, cooling the crystal effectively reduces the absorption.

The two obvious candidates (uniaxial birefringent) crystals are sapphire and quartz, because of their favorable optical properties in the FIR/submm. Sapphire is chosen over quartz due to its larger difference between ordinary and extraordinary refractive indices ($\Delta n_{e-o} \approx 0.32$ for sapphire, and ≈ 0.032 for quartz; Loewenstein et al. 1973), which implies a smaller thickness for the substrates (see Equation 1). Since quartz and sapphire have a comparable level of absorption at cryogenic temperatures in the wavelength range of 200–600 μm (Loewenstein et al. 1973), thinner substrates are desirable to minimise absorption losses. Nonetheless, the thin sapphire substrates chosen for the BLASTPol HWP do indeed show appreciable absorption, especially at the shortest wavelengths (250 μm band; see Section 3).

The five slabs of the Pancharatnam (1955) design all have the same thickness. To cover the broad wavelength range of 200–600 μm , a substrate thickness is chosen to produce a HWP at the central wavelength of the central band, 350 μm . By using the values of the refractive indices for cold sapphire published by Loewenstein et al. (1973) and Cook & Perkowitz (1985, $\Delta n_{e-o}^{350 \mu\text{m}} \approx 0.32$), and imposing the required phase shift of 180° between the two orthogonal polarisations travelling through the plate, Equation 1 yields for the thickness of a single substrate a value ~ 0.547 mm. The nearest available thickness on the market is 0.5 mm. A deviation of ~ 0.047 mm from the desired thickness translates to a departure of $\sim 15^\circ$ from the ideal phase shift of 180° at 350 μm , which is approximately what we measure (see Fig. 22). We briefly discuss the implications of this systematic effect at the end of Section 4.3.

The orientation of the optic axis on each sapphire substrate is determined with a polarising Fourier transform spectrometer (pFTS hereafter), which is briefly described in Section 3.1. Each substrate is rotated between two aligned polarisers at the pFTS output until a maximum signal is achieved. The use of two polarisers avoids any complication from a partially polarised detecting system and any cross polarisation incurred from the pFTS output mirrors. The HWP is assembled by marking the side of each substrate with its reference optic axis and rotating each element according to the Pancharatnam design described in the previous section. The stack of five carefully-oriented sapphire substrates, interspersed with 6 μm layers of polyethylene, are bonded together with a hot-pressing technique used in standard FIR/submm filter production (Ade et al. 2006). The polyethylene has negligible effects on the final optical performance of the HWP, because when heated it seeps into the roughened surfaces of the adjacent substrates.

In order to improve the robustness of the bond, the individual substrates are sandblasted with aluminium oxide (Al_2O_3) prior to fusion; this procedure dramatically improves the grip of the polyethylene between adjacent crystal surfaces. Careful cleansing and degreasing of all the crystal surfaces is required after sandblasting; in particular, we found trichloroethylene to be most effective in removing the traces of oily substances due to the sandblasting process.

The thickness of the resulting stack (uncoated HWP) is 2.55 ± 0.01 mm; its diameter is 100.0 ± 0.1 mm. A two-layer broadband anti-reflection coating (ARC), necessary to maximise the in-band transmission of the HWP, is also

³ The HWP designed for the mm-wave E and B EXperiment (EBEX; Matsumura et al. 2009; Reichborn-Kjennerud et al. 2010) is nominally slightly more achromatic, with a $\sim 110\%$ bandwidth. However, a comprehensive spectral characterisation of the final (as-flown) AR-coated HWP assembly has yet to be published.

hot-pressed to the front and back surfaces of the assembled plate, again using $6\text{ }\mu\text{m}$ layers of polyethylene. The layer adjacent to the sapphire is an artificial dielectric metamaterial (ADM) composed of metal-mesh patterned onto polypropylene sheets (Zhang et al. 2009), while the outer layer is a thin film of polytetrafluoroethylene (PTFE). The thickness of the final stack (coated HWP) is $2.80 \pm 0.01\text{ mm}$. The diameter of the ARC is set to $88.0 \pm 0.1\text{ mm}$, slightly smaller than that of the HWP to avoid any contact between the coating and the HWP mount (see Fissel et al. 2010); the ARC is bonded concentrically to the HWP and thus its diameter defines the optically-active area of the HWP.

Because of the thermal expansion mismatch between the sapphire and the polypropylene, the HWP assembly has been cryogenically cycled numerous times prior to the flight to test the robustness of the bond at liquid helium temperatures. The HWP has been successfully installed in the BLASTPol cryogenic receiver and has flown from a balloon platform for about ten days, without delamination of the ARC or damage to the assembly.

However, for cryogenic crystal HWPs larger in diameter than the BLASTPol one, the application of a metal-mesh ADM as an ARC has proven extremely challenging. Therefore, extending previous work by Pisano et al. (2008), we have recently designed and realised a prototype polypropylene-embedded metal-mesh broadband achromatic HWP for mm wavelengths (Zhang et al. 2011); this will allow next generation experiments with large-aperture detector arrays to be equipped with large-format ($\gtrsim 20\text{ cm}$ in diameter) HWPs for broadband polarisation modulation.

3 SPECTRAL CHARACTERISATION

3.1 Introduction

We fully characterise the spectral performance of the BLASTPol HWP by using a pFTS of the Martin-Puplett (1970) type. The source is an incoherent mercury arc lamp with an aperture of 10 mm , whose emission is well approximated by a blackbody spectrum at $T_{\text{eff}} \approx 2000\text{ K}$; a low-pass filter blocks radiation from the source at wavelengths shorter than $\sim 3.4\text{ }\mu\text{m}$. The interferometer is equipped with a P1⁴ beam divider, a P2 input polariser (at the source), and a P10 output polariser. The pFTS has a (horizontally) polarised output focused beam with $f/3.5$ or, in other words, a converging beam with angles $\theta \lesssim 8^\circ$.

As we will show in the next sections, the pFTS allows us to measure the HWP performance as a function of frequency and incoming polarisation state. Furthermore, because of the strong dependence of the sapphire absorption coefficient on temperature, we measure the spectral response of the HWP both at room (Section 3.2) and cryogenic temperatures ($\sim 120\text{ K}$; Section 3.3). Ultimately, we want to retrieve the frequency-dependent HWP Mueller matrix and phase shift, which, in turn, determine its spectral response and modulation efficiency.

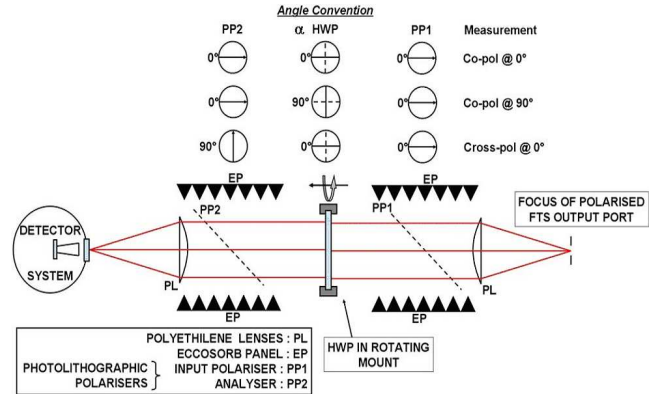


Figure 2. Schematic drawing of the room-temperature spectral measurements setup. The horizontally polarised output of a pFTS feeds into a polyethylene lens that creates a quasi-parallel beam and is then refocused onto the horn aperture of the bolometric detector. Two polarisers alternatively parallel and perpendicular create the necessary polarisation selection for the “co-pol” and “cross-pol” sets of measurements. The arrows for PP1 and PP2 indicate the selected polarisation, so that the wire grid orientations are perpendicular to the arrows. (from Zhang et al. 2011).

3.2 Room-temperature measurements

The schematic drawing of the room-temperature measurement configuration is shown in Fig. 2. In the following, we describe each element in sequential order from the polarised pFTS output to the detector system.

In order to measure the HWP performance at near-normal incidence, we use a planar convex polyethylene lens (with focus at the position of the output pFTS image) to generate a quasi-parallel beam section; a second lens refocuses the beam onto the horn aperture of the detector system. The maximum range of incident angles is thus limited by the input source aperture (10 mm), a beam spread of only 1.6° . This ensures an even illumination of the entire HWP optically-active area, as if it were inside the BLASTPol optics box (see Fissel et al. 2010; Pascale et al. 2012).

The HWP is placed centrally in the collimated beam section between two P10 polarisers (PP1 and PP2), which are tilted by 45° with respect to the optical axis to avoid standing waves between the optical elements. This tilt introduces four ports that are optically terminated with a close to ideal blackbody, Eccosorb AN72 absorber⁵. The efficiency of these polarisers is separately determined to exceed 99.8% over the range of frequencies of interest, with a cross-polarisation of less than 0.1%. The polarisers are initially aligned with respect to each other, with the grid wires vertical (thus selecting horizontal polarisation) with respect to the optical bench, in order to avoid any projection effect when tilted.

Following the convention depicted in Fig. 2, measurements with aligned polarisers are referred to as “co-pol” transmission, T_{cp} . As shown in the next section, the HWP has a complementary response when the output polariser PP2 (analyser) is rotated by 90° about the optical axis of

⁴ We denote with $P_n [\mu\text{m}]$ the period of a photolithographed wire grid polariser, which has $n/2$ copper strips with $n/2$ gaps on a $1.5\text{ }\mu\text{m}$ mylar substrate.

⁵ Emerson and Cuming, Microwave Products, <http://www.eccosorb.com/>.

the system (i.e., horizontal wires, selecting vertical polarisation); data taken with this configuration are also necessary to completely characterise the HWP, and are referred to as “cross-pol” transmission⁶, T_{xp} .

Common to both the warm and cold measurements is the requirement to position and rotate the HWP accurately with respect to its optical axis. When at room temperature, the HWP is held and rotated by a motorised rotating mount positioned centrally between the two tilted polarisers. The mount has a fixed orientation with respect to the optical axis of the system; we position it so that the collimated beam has normal incidence on the HWP (within 1°), and evenly illuminates its surface. The electronically-controlled rotating mount can rotate the HWP about its optical axis to obtain the polarisation modulation; the resolution of the digital angular encoder on the rotation angle is 0.001° (a CAD drawing of the optical bench setup, including the motorised rotating mount, can be found in Fig. 1 of Pisano et al. 2006).

Finally, the detecting system used is a 4.2 K liquid helium cooled indium antimonide (InSb) detector, which is cryogenically filtered to minimise photon noise. The spectral coverage of the data is thus defined by the cut-off frequency of the light collector waveguide (5 cm^{-1}) and by two low-pass filters in the cryostat housing the bolometric detector (60 cm^{-1}). We pay particular attention to ensure the absorption of any diffracted or reflected stray radiation. Besides terminating all unused optical ports as described above, additional Eccosorb AN72 covers all the exposed metallic surfaces close to the optical path.

The rapid scan system records interferograms with a $8 \mu\text{m}$ sampling interval over a 10 cm optical path difference, at a scan speed of 1 cm s^{-1} ; this results in a Nyquist frequency of 625 cm^{-1} and a spectral resolution of 0.05 cm^{-1} .

A first dataset is obtained in co-pol configuration by scanning the spectrometer in the absence of the HWP, which we refer to as the background spectrum. This dataset defines the pFTS reference spectral envelope, and it is the set against which all the following spectra are divided in order to account for the spectral features of the source, pFTS optics, detector system, and laboratory environment (i.e., water vapour). Subsequently, the HWP is inserted in between the tilted polarisers in co-pol configuration, and spectra are acquired at many different HWP rotation angles (resulting in a data cube). To enhance the spectral signal-to-noise ratio, each dataset at a given angle is obtained by computing the Fourier transform of an (apodised and phase-corrected) average of 60 interferograms with the mirror scanned in both the forward and backward directions. As anticipated, the resulting spectra are divided by the background dataset, which in turn is the average of three spectra, to obtain the transmission of the coated HWP alone as a function of frequency.

Because these data are collected over several hours, the amount of water vapour in the room is likely to slightly change with time; we account for this by taking background spectra approximately every hour and dividing the HWP spectra taken within that hour only by the corresponding background dataset. Nevertheless, discernible residuals from

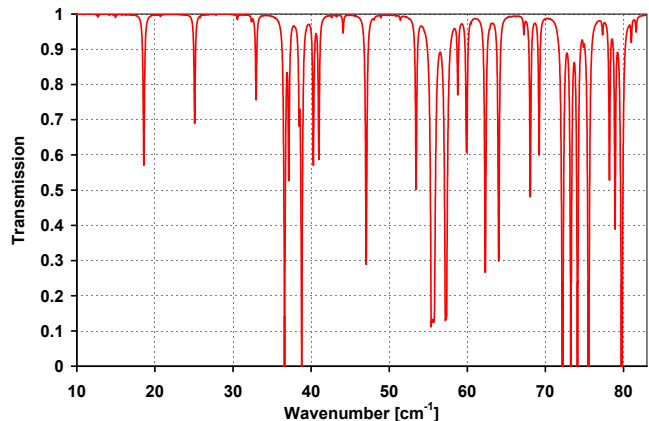


Figure 3. Synthetic transmission spectrum from an atmospheric model, in arbitrary units. Provided by Ade (2009, private communication).

atmospheric features can still be appreciated in the final HWP spectra, especially at wavenumbers $k \gtrsim 30 \text{ cm}^{-1}$ (the BLASTPol $250 \mu\text{m}$ band). We use a synthetic atmospheric transmission spectrum (provided by Ade 2009, private communication; shown in Fig. 3) to correct the original spectra by concurrently scaling the amplitude of the most prominent features, which are due to water vapour. We find that while some of the spectra do not need any correction at all, others need to be corrected by as much as $\sim 15\%$; the corrected spectra are shown in Fig. 4, where each line is a spectrum at a different rotation angle of the HWP (in the range $\theta = 0^\circ - 332^\circ$).

An ideal HWP modulates the polarisation at 4θ , therefore in a complete revolution there are four maxima (and minima), two for each of the birefringent axes. The zero angle in this case coincides with the HWP maximum, which is the HWP angle at which we measure maximum total power on the detector; this of course includes signal outside of the HWP bands (in the range $5 - 60 \text{ cm}^{-1}$). As we show in Section 4.2, the position of the equivalent axes of the sapphire plate stack (and hence the position of the HWP maxima/minima) depends upon the wavelength. Therefore the HWP maxima (and minima) we assign while taking spectra are just rough approximations. Although we increase the angle sampling rate in the vicinities of a maximum or minimum, in order to fully characterise the HWP it is not necessary to take spectra *exactly* at its maxima or minima.

Due to polarisation symmetry, no appreciable change should be observed in pairs of datasets taken at angles that are 180° apart. We verify that the experimental setup is symmetric with respect to the HWP rotation by comparing spectra taken, for instance, near the two maxima, at $\theta_1^{\text{max}} = [0^\circ, 180^\circ]$ and at $\theta_2^{\text{max}} = [88^\circ, 268^\circ]$. The fact that the curves are superimposed confirms that there are no artifacts arising from misalignments in the optical setup.

Although we do correct for the residual contaminations due to atmospheric features, which mainly affect the shorter BLASTPol wavelengths, we cannot rule out the possibility that some of the spectral fringes may still be altered. Furthermore, and more importantly, these spectra show significant in-band transmission loss due to the absorption from sapphire at room temperature, which becomes more promi-

⁶ We note that this definition of cross-pol may differ from other conventions adopted in the literature (e.g., that of Masi et al. 2006, who operate without a HWP).

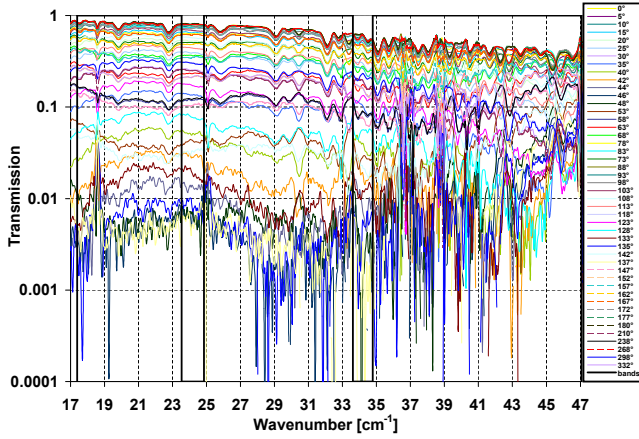


Figure 4. Measured co-pol transmission spectra of the coated BLASTPol HWP at room temperature. Each line is obtained at a different HWP rotation angle by computing the Fourier transform of an (apodised and phase-corrected) average of 60 interferograms. The resulting spectra are corrected for residual contaminations due to atmospheric features by using the synthetic spectrum shown in Fig. 3. The solid vertical black lines show the approximate extent of the three BLASTPol bands.

nent with increasing frequency. Because of these two reasons, we do not take cross-pol spectra at room temperature and repeat our measurements with the HWP in a vacuum cavity, at temperatures as low as currently possible with the experimental apparatus at our disposal.

3.3 Cold measurements

The experimental setup for spectral measurements of the cold HWP is substantially different than that described in the previous section, except for the radiation source and the main pFTS module.

We position the HWP in a liquid nitrogen-cooled removable module retrofitted in the vacuum cavity at the output port of the pFTS; a photograph and a brief description of the module, which we refer to as “cold finger”, are given in Fig. 5. After the roughly two hours needed for the cold finger module to thermalise, its base plate reaches temperatures close to 77 K, while the HWP holder thermalises at about 120 K, despite the careful thermal insulation and link to the base plate. Other cryogenic tests conducted by bonding a thermometer at the center of a single slab of sapphire ensure that the temperature measured at the edge of an aluminium or copper holder closely matches that of the sapphire substrate at its center.

While maintaining a constant level of liquid nitrogen in the cold finger, we can characterise the spectral response of the cold HWP, by rotating it inside the vacuum cavity with a rotation angle resolution of 0.06° . In this configuration, the P10 output polariser of the pFTS acts as PP1 in the room temperature setup (see Fig. 2), while a second P10 polariser (analyser, acting as PP2) is installed at the exit port of the vacuum cavity. On the outside of the cavity, the cryostat housing the bolometric detector is connected with no air gaps to the exit port. This time we use a composite bolometer cooled to 1.5 K by pumping on the liquid helium

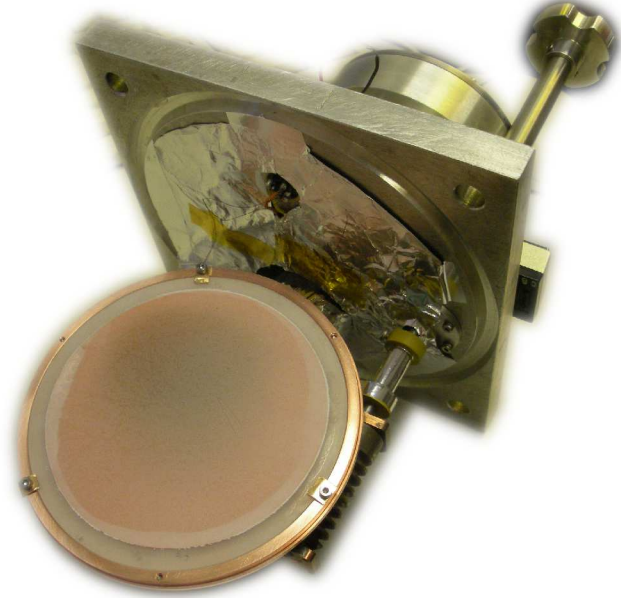


Figure 5. Photograph of the “cold finger” module, which fits in the vacuum cavity at the output port of the pFTS. The central cylinder is hollow and has to be regularly replenished with liquid nitrogen to maintain the temperature of the HWP at ~ 120 K. Aluminium insulation and a thick copper strap improve the thermal performance of the module. Two thermometers monitor the temperature at the bottom of the cylinder (base plate) at the edge of the copper HWP holder. The rotator is manually driven via a gear train and a vacuum-seal shaft leading to a manual knob outside the module. The resolution of the analogue encoder on the rotation angle is 0.06° . The presence of a thermometer on the rotating element prevents rotations greater than $\sim 180^\circ$.

bath; this detector is again cryogenically low-pass filtered at 60 cm^{-1} to minimise photon noise.

Over two days of measurements, we acquire data cubes for co-pol (Figs. 6 and 8) and cross-pol (Figs. 7 and 9) transmissions using exactly the same parameters as quoted in the previous section, except for the scan speed, which we increase to 2 cm s^{-1} to speed up the measurement process at no expense to the quality of the spectra. The background dataset is obtained in co-pol configuration by scanning the spectrometer in the absence of the cold finger. Because of the controlled environment in the vacuum cavity, our measurements are now much less susceptible to the external environment; however, we repeat background scans at the very end of our measurement session to monitor drifts in the bolometer responsivity and other potential systematic effects. Prior to inserting the cold finger in the cavity, we characterise the instrumental cross-pol of this setup by rotating PP2 by 90° in cross-pol configuration and acquiring three spectra. By averaging these cross-pol spectra and dividing by the co-pol background, we measure a cross-pol level of 0.2% or less across the entire spectral range of interest ($5\text{--}60 \text{ cm}^{-1}$); we include the resulting cross-pol spectrum in Figs. 6 and 7 (dark pink line).

In the surfaces depicted in Figs. 8 and 9, slices of the data cube along the wavenumber axis constitute the measured spectra for different angles of the HWP, while slices along the angle axis represent the modulation function of the wave plate at a given frequency or, more precisely, within a

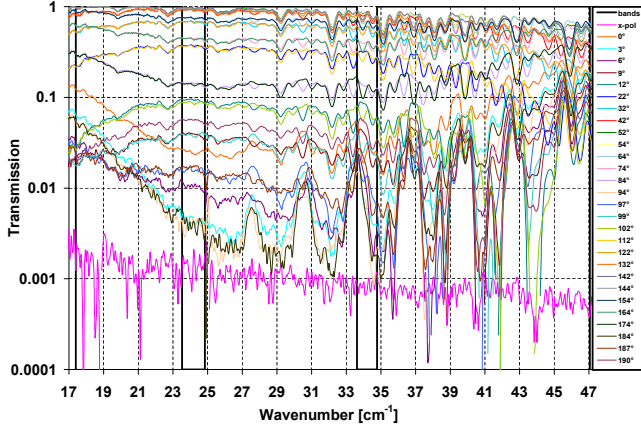


Figure 6. Measured co-pol transmission spectra equivalent to those shown in Fig. 4 but with the HWP at ~ 120 K.

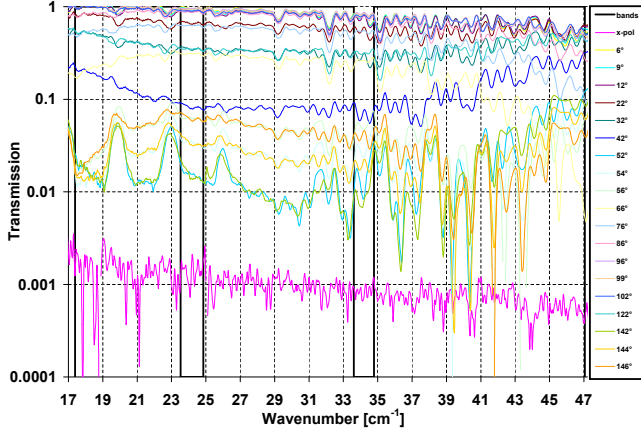


Figure 7. Measured spectra of the HWP at ~ 120 K equivalent to those shown in Fig. 6 but for cross-pol transmission.

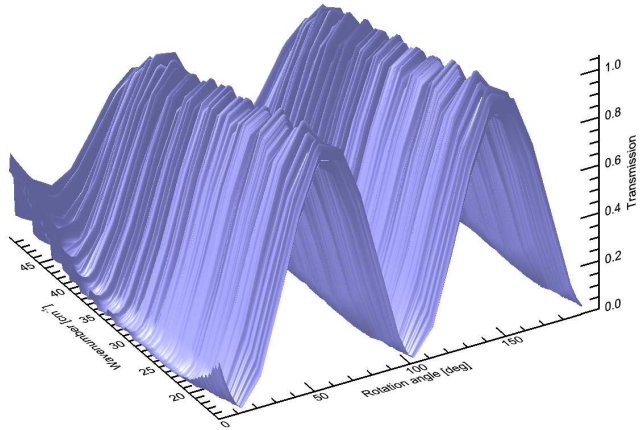


Figure 8. Data cube represented by a surface obtained by stacking a set of spectral co-pol transmissions of the HWP at different angles. Each measured spectra (as shown in Fig. 6) is a slice of the surface perpendicular to the angle axis.

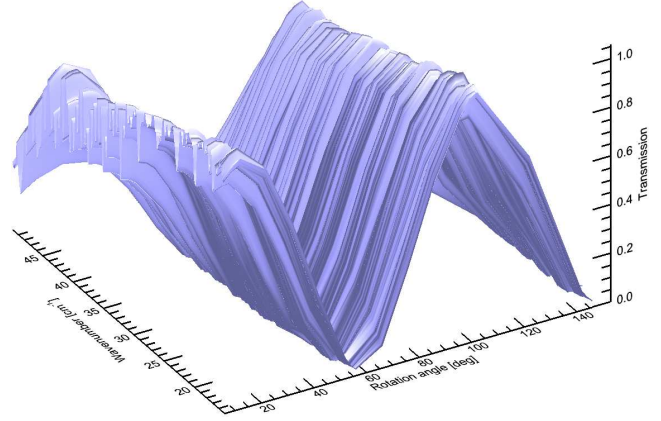


Figure 9. Equivalent data cube to that shown in Fig. 8 but for cross-pol transmission. Note how the two surfaces are complementarily in counterphase to each other. Each measured spectra (as shown in Fig. 7) is a slice of the surface perpendicular to the angle axis.

narrow band of frequencies defined by a combination of spectral resolution and the spectrometer's instrument response function.

The features visible in all spectra (including those shown previously in Fig. 4) are spectral fringes due to standing waves generated inside the stack of dielectric substrates (even with a quasi-perfect impedance matching coating on the outer surfaces); the presence of several interspersed layers of polyethylene enhances the amplitude of the fringes by introducing small amounts of absorption at every internal reflection.

3.4 Uncertainties on the measured spectra

Because we average 60 interferograms to obtain the final spectrum at each HWP position, the statistical uncertainty associated with the average on a single dataset is found to be negligible, as expected. Rather, we decide to average together all the available background interferograms that are collected over one day of measurements, and take their statistical dispersion as our estimate of the uncertainty associated with all the spectra collected on that day. Because the thermodynamic conditions in the cavity under vacuum are not susceptible to changes in the external environment, this procedure allows us to account for drifts in the bolometer responsivity and other potential systematic effects. We show in Fig. 10 the mean background spectra and the associated error for the co-pol and cross-pol measurement sessions. These errors are used in Section 4 to estimate the uncertainties on the HWP Mueller matrix coefficients.

3.5 Modulation function and efficiency

We can reduce the dependence on frequency of our data cubes by integrating over the spectral bands of BLASTPol, as follows:

$$\overline{T}_{\text{cp}}^{\text{ch}}(\theta) = \frac{\int_0^\infty \Sigma^{\text{ch}}(\nu) T_{\text{cp}}(\theta, \nu) d\nu}{\int_0^\infty \Sigma^{\text{ch}}(\nu) d\nu}. \quad (2)$$

Here the superscript “ch” refers to one among 250, 350, and 500 μm , $\Sigma^{\text{ch}}(\nu)$ is the measured spectral response of each of

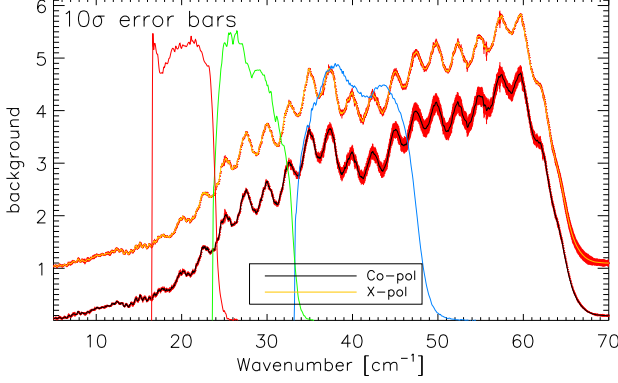


Figure 10. Noise estimation for the spectra shown in Figs. 6 and 7. We plot the mean background spectra (in arbitrary units) for the co-pol (black solid line) and cross-pol (yellow solid line, shifted by 1 in the positive y direction for visual clarity) as a function of wavenumber. The (10σ) error bars (in red) are quantified as the statistical error on the mean. Also shown for reference is the relative spectral response of the three BLASTPol channels, in arbitrary units. Henceforth, we adopt a colour code in the plots whereby curves referring to the three BLASTPol bands, 250, 350, and $500\ \mu\text{m}$ are drawn in blue, green, and red, respectively.

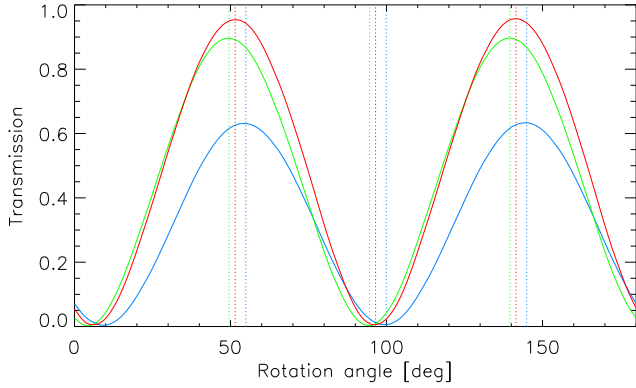


Figure 11. Band-integrated co-pol modulation functions of the BLASTPol HWP at $\sim 120\ \text{K}$. The curves show the HWP polarisation modulation functions for a fully polarised source (with a flat spectrum) parallel to the analyser in the three spectral bands. Note how the positions of the maxima (and minima) depend on the wavelength, even when considering a flat-spectrum polarised input source; the dotted vertical lines show the band-integrated positions of the HWP extrema (shown in Fig. 19), which result from the fitting routine described in the next sections.

the BLASTPol bands (see Pascale et al. 2008), and $T_{\text{cp}}(\theta, \nu)$ are points on the co-pol surface depicted in Fig. 8. A similar expression can be written for the cross-pol band-integrated transmission. By performing this integration at every angle for which spectral data have been obtained, the interpolation of these data points will result in the modulation functions of the HWP at $\sim 120\ \text{K}$ for each of the BLASTPol spectral bands; these curves are shown in Fig. 11 for co-pol and in Fig. 12 for cross-pol.

The modulation curves presented here assume that the incoming polarised radiation has no dependence on frequency, or in other words that the input source has a flat spectrum in frequency. Equation 2 can be generalised to include the known (or assumed) spectral signature of a given

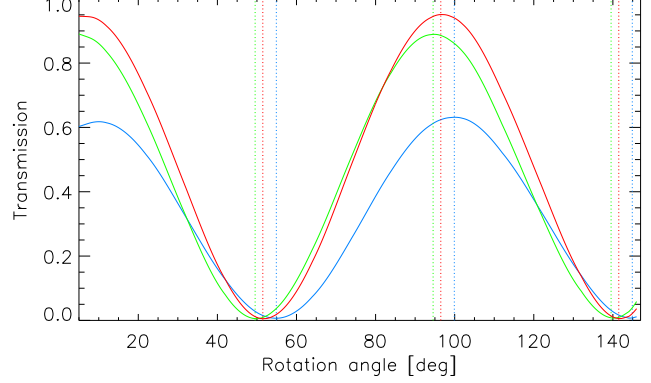


Figure 12. Band-integrated modulation functions equivalent to those shown in Fig. 11 but for cross-pol transmission.

astronomical or calibration source (see also e.g., Novak et al. 1989, Equation 2). More generally, all the band-averaged quantities that we have defined here and will be defined in the following are potentially affected by the spectral shape of the input source. However, we will see how the HWP transmission and modulation efficiency are very weakly dependent on the spectral index of the input source, whereas the position of the equivalent axes of the sapphire plate stack is more significantly affected (see also the analysis carried out by Savini et al. 2009), especially at 250 and $500\ \mu\text{m}$.

Figs. 11 and 12 clearly show that there is a significant dependence of the position of the HWP maxima and minima upon frequency, even when considering a flat-spectrum polarised input source. These effects are particularly important for a “HWP step and integrate” experiment such as BLASTPol, and a careful post-flight polarisation calibration must be performed by using all the information available from the pre-flight characterisation of the HWP. We begin to tackle this problem in the next section, where we outline a relatively simple solution to account for most of the HWP non-idealities in the data-analysis pipeline, and in particular in the map-making algorithm (see Section 5).

The spectral transmission datasets of the HWP cooled to $\sim 120\ \text{K}$, when compared to those taken with the HWP at room temperature (Fig. 4), show a definite abatement of the in-band losses due to absorption from sapphire, as expected. However the effect is still appreciable, especially above $\sim 25\ \text{cm}^{-1}$. As we will show in the following, we have independent evidence that the residual absorption nearly vanishes when the sapphire is further cooled to $4\ \text{K}$, as it is when the HWP is installed in the BLASTPol cryostat. While it is not currently feasible for us to measure the spectral response of the HWP cooled to $4\ \text{K}$, the unique quality and completeness of our dataset allow us to fully characterise the performance of the BLASTPol HWP.

We extrapolate our “cold” dataset to $4\ \text{K}$, using a combination of the analytical expression and the data points taken from the literature and reported in Fig. 13. The HWP modulation efficiency is defined as $(T_{\text{cp}}^{0^\circ} - T_{\text{xp}}^{0^\circ}) / (T_{\text{cp}}^{0^\circ} + T_{\text{xp}}^{0^\circ})$, where the “co-pol” and “cross-pol” transmissions, $T_{\text{cp}}^{0^\circ}$ and $T_{\text{xp}}^{0^\circ}$, are the spectral transmission response of the HWP, with its axis at 0° , between parallel and perpendicular polarisers, respectively. The inferred co-pol/cross-pol transmissions and modulation efficiency of the BLASTPol HWP

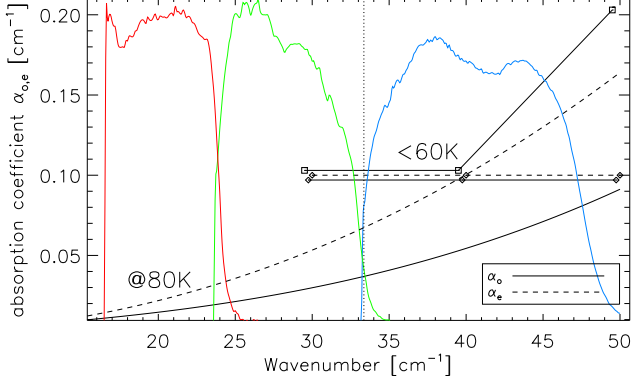


Figure 13. Ordinary (solid lines) and extraordinary (dashed lines) sapphire absorption coefficient as a function of wavenumber, at cryogenic temperatures. The two analytical relations covering the whole frequency range are derived by Savini (2010, private communication; see also Savini et al. 2006) from a set of spectral measurements of a sapphire sample at 80 K, and, strictly speaking, only apply for frequencies $\lesssim 1$ THz (dotted vertical line). For reference, we also plot measurements from Loewenstein et al. (1973, diamonds) at 1.5 K and Cook & Perkowitz (1985, squares) at 60 K, displaced in x by 0.25 cm^{-1} and in y by 0.003 cm^{-1} for visual clarity; the lines connecting these data points follow the convention shown in the legend.

(with its axis at 0°) at 4 K are shown in Fig. 14. For a flat-spectrum input source, the band-integrated transmission of the HWP at its maxima is ~ 0.87 , ~ 0.91 , and ~ 0.95 at 250, 350, and $500 \mu\text{m}$, respectively; whereas the band-integrated cross-pol is $\lesssim 0.5\%$, $\lesssim 0.2\%$, and $\lesssim 0.5\%$, respectively; finally, the band-integrated modulation efficiency is $\sim 98.8\%$ $\sim 99.5\%$, and $\sim 99.0\%$, respectively.

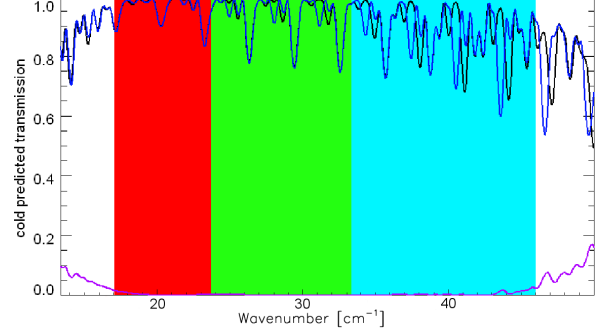
4 EMPIRICAL MODELLING

The final goal of this section is to provide a set of usable parameters that completely describe the performance of the HWP as measured in the laboratory. This set of parameters consists of the 16 coefficients of the Mueller matrix of a generic HWP, and the actual phase shift. For an ideal HWP, the Mueller matrix at $\theta = 0^\circ$ reads (Collett 1993)

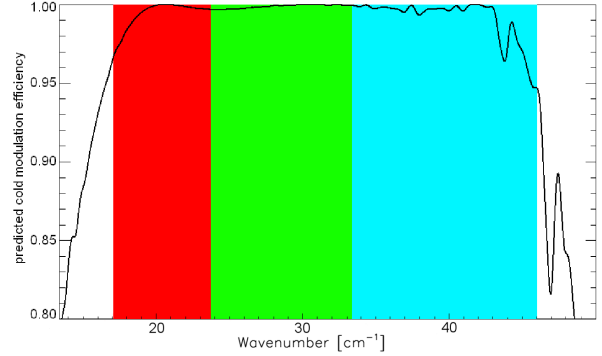
$$\mathcal{M}_{\text{HWP}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \quad (3)$$

and the phase shift is $\Delta\varphi = 180^\circ$.

For a real HWP, these parameters always depart from the ideal case to some extent, and certainly depend upon frequency. In the following we describe an empirical model that we develop specifically for the characterisation of the BLASTPol HWP, though we note that it can be applied to any HWP to recover its frequency-dependent descriptive parameters. Such an empirical model is complementary to the physical and analytical one developed by Savini et al. (2006, 2009), which produces an analogous output by modelling the non-idealities of the components of the HWP assembly and their optical parameters.



(a) The predicted transmissions through the cold HWP as a function of wavenumber. The black line shows the HWP transmission, $T_{\text{cp}}^{0^\circ}$, between two parallel polarisers ($Q = 1 \rightarrow Q = 1$) with the HWP axis at 0° . The dark blue line shows $Q = -1 \rightarrow Q = -1$ in the same reference frame (or equivalently $Q = 1 \rightarrow Q = 1$ with the HWP axis at 90°). The purple line shows the transmission, $T_{\text{xp}}^{0^\circ}$, with the HWP axis at 0° between two perpendicular polarisers.



(b) Predicted modulation efficiency of the cold HWP as a function of wavenumber, obtained as $(T_{\text{cp}}^{0^\circ} - T_{\text{xp}}^{0^\circ}) / (T_{\text{cp}}^{0^\circ} + T_{\text{xp}}^{0^\circ})$. Note that the y -axis scale ranges from 0.8 to 1.

Figure 14. Predicted performance of the BLASTPol HWP at 4 K, extrapolated from a set of spectral data collected with the HWP cooled to ~ 120 K (see Section 3.3). “Co-pol” and “cross-pol” transmissions, T_{cp} and T_{xp} , are defined as in Fig. 2. The approximate extent of the BLASTPol bands is also indicated.

4.1 Mueller matrix characterisation

By recalling the Stokes formalism, we can formalise the experimental apparatus described in Sections 3.2 and 3.3 as a series of matrix products, as follows:

$$S_{\text{out}}^{\text{cp}} = \vec{D}^T \cdot \mathcal{M}_p^h \cdot \mathcal{R}(-\theta) \cdot \mathcal{M}_{\text{HWP}} \cdot \mathcal{R}(\theta) \cdot \vec{S}_{\text{in}}^h; \quad (4)$$

$$S_{\text{out}}^{\text{xp}} = \vec{D}^T \cdot \mathcal{M}_p^v \cdot \mathcal{R}(-\theta) \cdot \mathcal{M}_{\text{HWP}} \cdot \mathcal{R}(\theta) \cdot \vec{S}_{\text{in}}^h. \quad (5)$$

Here \vec{D} is the Stokes vector for a bolometric (polarisation insensitive) intensity detector, \mathcal{M}_p^h is the Mueller matrix of an ideal horizontal polariser, \mathcal{M}_p^v is that of an ideal vertical polariser, $\mathcal{R}(\theta)$ is the generic Mueller rotation matrix, and \vec{S}_{in}^h is the horizontally polarised input beam from the pFTS.

By expanding all the matrices in Equation 4,

$$S_{\text{out}}^{\text{cp}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \quad (6)$$

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\theta) & \sin(2\theta) & 0 \\ 0 & -\sin(2\theta) & \cos(2\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} a_{00} & a_{01} & a_{02} & a_{03} \\ a_{10} & a_{11} & a_{12} & a_{13} \\ a_{20} & a_{21} & a_{22} & a_{23} \\ a_{30} & a_{31} & a_{32} & a_{33} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\theta) & -\sin(2\theta) & 0 \\ 0 & \sin(2\theta) & \cos(2\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix},$$

we can compute the products and rearrange as

$$S_{\text{out}}^{\text{cp}} = \frac{1}{2} [2a_{00} + a_{11} + a_{22} + 2(a_{01} + a_{10}) \cos 2\theta + (a_{11} - a_{22}) \cos 4\theta - 2(a_{02} + a_{20}) \sin 2\theta - (a_{12} + a_{21}) \sin 4\theta] = A + B \sin 2\theta + C \cos 2\theta + D \sin 4\theta + E \cos 4\theta, \quad (7)$$

with

$$\begin{aligned} A &\equiv a_{00} + \frac{a_{11}}{2} + \frac{a_{22}}{2}, \\ B &\equiv -(a_{02} + a_{20}), \quad C \equiv a_{01} + a_{10}, \\ D &\equiv -\frac{1}{2}(a_{12} + a_{21}), \quad E \equiv \frac{1}{2}(a_{11} - a_{22}). \end{aligned} \quad (9)$$

Similarly, noting that

$$\mathcal{M}_{\text{p}}^{\text{v}} = \begin{pmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

we rearrange Equation 5 as

$$S_{\text{out}}^{\text{xp}} = A' + B' \sin 2\theta + C' \cos 2\theta + D' \sin 4\theta + E' \cos 4\theta, \quad (10)$$

with

$$\begin{aligned} A' &\equiv a_{00} - \frac{a_{11}}{2} - \frac{a_{22}}{2}, \\ B' &\equiv a_{20} - a_{02}, \quad C' \equiv a_{01} - a_{10}, \\ D' &\equiv \frac{1}{2}(a_{12} + a_{21}), \quad E' \equiv \frac{1}{2}(a_{22} - a_{11}). \end{aligned} \quad (11)$$

Finally, by performing linear combinations of the quantities defined in Equations 9 and 11, one can write the individual elements that compose the Mueller matrix of a generic HWP as

$$\begin{aligned} a_{00} &= \frac{1}{2}(A + A'), \quad a_{01} = \frac{1}{2}(C + C'), \\ a_{10} &= \frac{1}{2}(C - C'), \quad a_{11} = \frac{1}{2}(A - A' + E - E'), \\ a_{02} &= -\frac{1}{2}(B + B'), \quad a_{20} = \frac{1}{2}(B' - B), \\ a_{22} &= \frac{1}{2}(A - A' - E + E'), \quad a_{12} = a_{21} = \frac{1}{2}(D' - D), \end{aligned} \quad (12)$$

where in the last equality we currently assume the symmetry of two coefficients, $a_{12} = a_{21}$. This degeneracy may be broken by imposing the conservation of energy, i.e. by requiring the output Stokes vector resulting from a generic polarised input travelling through the recovered HWP Mueller matrix to satisfy $I^2 = Q^2 + U^2$. Alternatively, the degeneracy

can be broken by taking spectra at an intermediate configuration between co- and cross-pol; this additional constraint will be included in a future work (Spencer et al., in preparation). Also, because our experimental setup is sensitive to linear but not circular polarisation, this method only allows us to constrain the 9 elements of the Mueller matrix associated with $[I, Q, U]$. The remaining 7 coefficients associated with V can only be measured with the use of a quarter-wave plate, which induces a phase shift of 90° between the two orthogonal polarisations travelling through the plate; this measurement is beyond the scope of this paper and not pertinent to the needs of BLASTPol.

We want to estimate the 9 coefficients derived in Equation 12 from the co-pol and cross-pol data cubes described in Section 3.3. Equations 8 and 10 encode a simple dependence of $S_{\text{out}}^{\text{cp}}$ and $S_{\text{out}}^{\text{xp}}$ upon θ , the HWP rotation angle. Therefore, for a given frequency, a fitting routine can be applied to the measured transmission curves as a function of θ , to determine the parameter sets $[A, B, C, D, E]$ and $[A', B', C', D', E']$ for the co-pol and cross-pol configurations, respectively. By repeating the fit for every frequency, we have an estimate of the 9 coefficients as a function of wavelength. However, this procedure does not allow us to associate any uncertainty to our estimates.

A better approach to this problem is to use a Monte Carlo simulation. We repeat the above fitting procedure 1000 times; every time we add to every individual transmission curve a realisation of white noise, scaled to the 1σ spectral uncertainty as estimated in Fig. 10, and compute the fit using this newly generated transmission curve. In addition, for every frequency we introduce a random jitter on the rotation angle that has a 1σ amplitude of 1° . The dispersion in the fitted parameters due to these two types of uncertainties, which are inherent to the measurement process, provides a realistic estimate of the uncertainty associated with each of the 9 coefficients. In particular, at each frequency, we produce 9 histograms of the 1000 fitted values. We use the mode of each distribution as our best estimate for the corresponding coefficient at that frequency, and the 68% confidence interval as the associated 1σ error.

In Fig. 15 we show a graphical representation of the 9-element Mueller matrix of the BLASTPol HWP at a given angle ($\theta = 0^\circ$), as a function of wavenumber. In Figs. 16, 17, and 18 we show the resulting histograms for the 9 coefficients at 20, 28.6, and 40 cm^{-1} , respectively (which are the central frequencies of the BLASTPol bands).

4.2 Position of the HWP equivalent axes

The behaviour of the coefficients as a function of wavenumber shown in Fig. 15 suggests that the position of the HWP equivalent axes, β_{ea} hereafter, may have an inherent frequency dependence, which we must investigate. β_{ea} can be readily retrieved at each frequency by locating the rotation angle that corresponds to the first minimum in the fitted transmission curve. Hence, β_{ea} is measured with respect to an arbitrary constant offset that is inherent to the specific experimental setup; we set this offset to be zero at 25 cm^{-1} . Operationally, this means that the HWP zero angle in the instrument reference frame (β_0 ; see Equation 17) must be calibrated using the $350 \mu\text{m}$ band. A plot of β_{ea} as a function of wavenumber is given in Fig. 19.

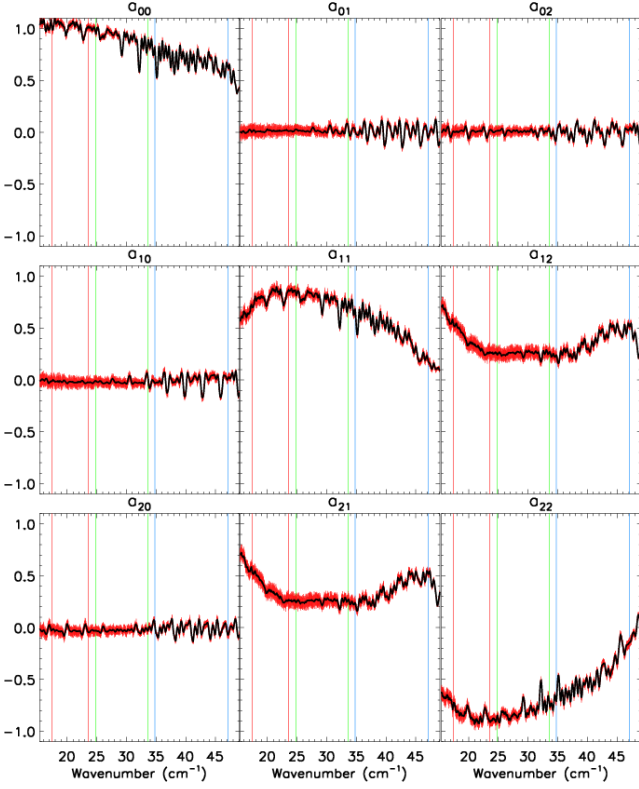


Figure 15. Graphical representation of the Mueller matrix of the BLASTPol HWP at a given angle ($\theta = 0^\circ$), as a function of wavenumber. The (10σ) error bars (in red) are quantified via a Monte Carlo, which accounts for random errors in the spectra of amplitude as given in Fig. 10, and random errors of amplitude 1° in the rotation angle.

As anticipated, it is of crucial importance to derive the band-averaged value of β_{ea} for input sources with different spectral signature, as follows:

$$\bar{\beta}_{\text{ea}}^{\text{ch}} = \frac{\int_0^\infty \Sigma^{\text{ch}}(\nu) \beta_{\text{ea}}(\nu) \varsigma(\nu) d\nu}{\int_0^\infty \Sigma^{\text{ch}}(\nu) \varsigma(\nu) d\nu}, \quad (13)$$

where we adopt the same notation as in Equation 2 and the known (or assumed) spectrum of an astronomical or calibration source is modelled as $\varsigma(\nu) \propto \nu^\alpha$. We compute Equation 13 for a range of spectral indices of interest: $\alpha = 0$ for a flat spectrum; $\alpha = 2$ for the Rayleigh-Jeans tail of a blackbody; $\alpha = 4$ for interstellar dust, modelled as a modified blackbody with emissivity $\beta = 2$ (Hildebrand 1983); and finally $\alpha = -2$ as a replacement for the mid-infrared exponential on the Wien side of a blackbody to account for the variability of dust temperatures within a galaxy (Blain 1999; Blain et al. 2003). The results of this analysis are shown in Fig. 19 and in Table 1.

As expected, the impact of different input spectral signatures is minimal at $350 \mu\text{m}$, where the HWP has been designed to function optimally (see Section 2.2); whereas the spectral dependence is more pronounced at 250 and $500 \mu\text{m}$, and, if neglected, it may lead to an arbitrary rotation of the retrieved polarisation angle on the sky of magnitude $2\bar{\beta}_{\text{ea}} = 10\text{--}15^\circ$ ($3\text{--}5^\circ$) at 250 (500) μm (see Equation 17).

We have thus confirmed that the dependence of the HWP equivalent axes upon wavelength is inherent to the

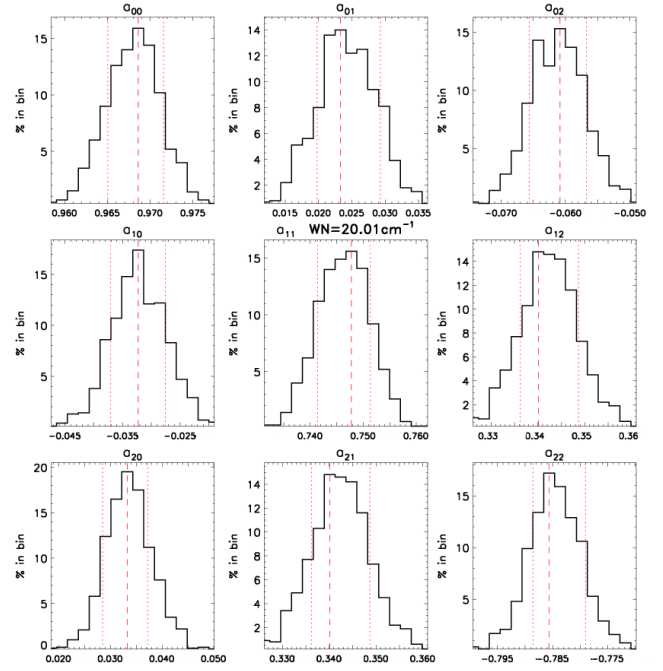


Figure 16. Histograms at 20 cm^{-1} (central frequency of the $500 \mu\text{m}$ BLASTPol band) resulting from the Monte Carlo fit of the HWP parameters. For every histogram, the dashed red line indicates the mode of the distribution, which we adopt as our best estimate for the corresponding coefficient at that frequency, while the two dotted red lines indicate the 68% confidence interval, which we use as the uncertainty on the retrieved coefficient.

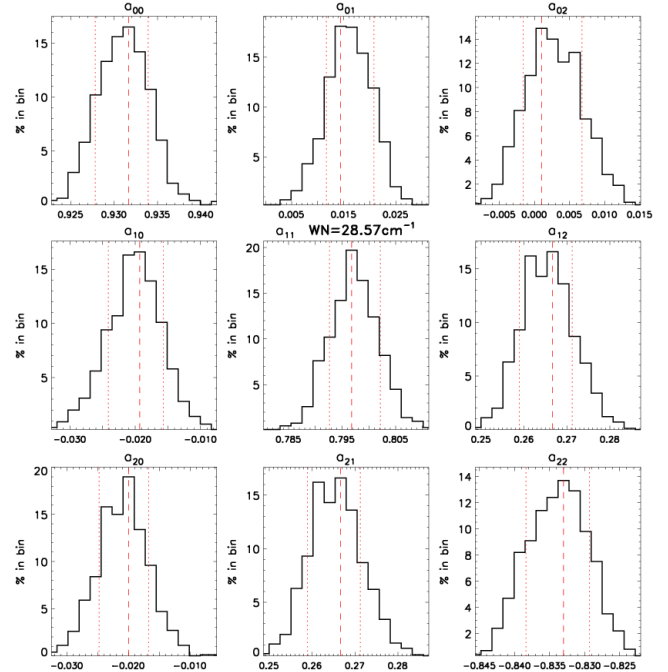


Figure 17. Equivalent histograms to those shown in Fig. 16 but at 28.57 cm^{-1} (central frequency of the $350 \mu\text{m}$ BLASTPol band).

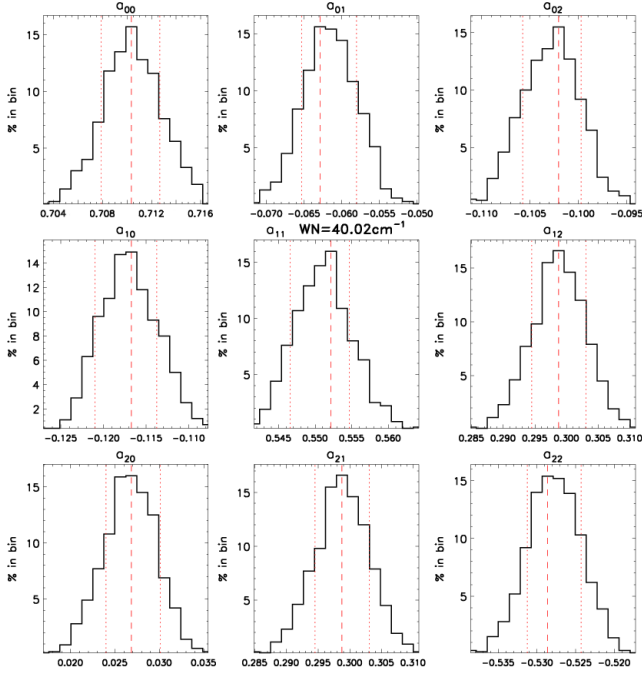


Figure 18. Equivalent histograms to those shown in Fig. 16 but at 40 cm^{-1} (central frequency of the $350 \mu\text{m}$ BLASTPol band).

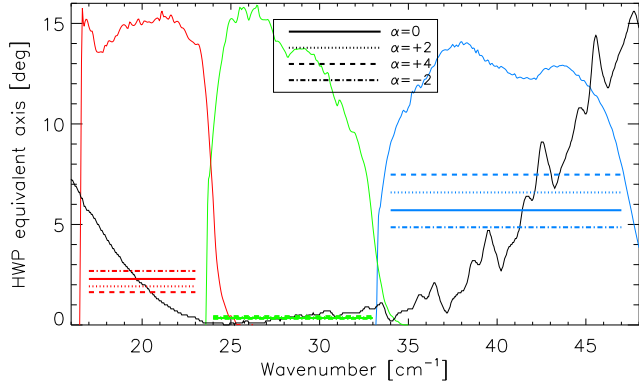


Figure 19. Position of the HWP equivalent axis, β_{ea} , as a function of wavenumber (solid black line). Note that this quantity is defined with respect to an arbitrary constant offset that is inherent to the specific experimental setup; we set this offset to be zero at 25 cm^{-1} . The band-averaged values for input sources with different spectral index (α ; see legend) are drawn as thick horizontal lines. Also shown for reference is the relative spectral response of the three BLASTPol channels, in arbitrary units.

| α | $\bar{\beta}_{\text{ea}}$ [deg] | | |
|----------|---------------------------------|-------------------|-------------------|
| | $250 \mu\text{m}$ | $350 \mu\text{m}$ | $500 \mu\text{m}$ |
| -2 | 4.9 | 0.30 | 2.7 |
| 0 | 5.7 | 0.35 | 2.3 |
| +2 | 6.6 | 0.39 | 1.9 |
| +4 | 7.5 | 0.44 | 1.6 |

Table 1. Band-averaged position of the HWP equivalent axis for sources with different spectral index. The input source is assumed to have a spectrum $\varsigma \propto \nu^\alpha$.

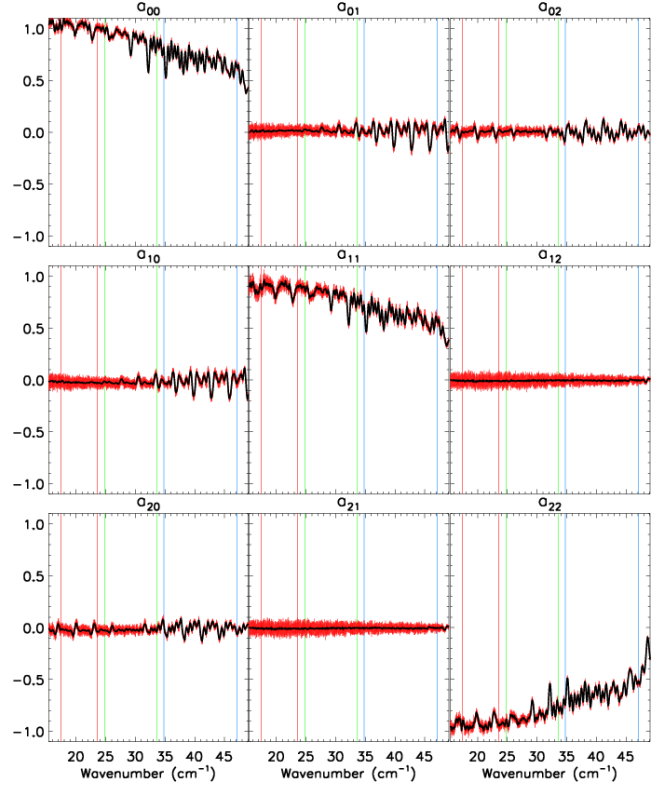


Figure 20. Graphical representation of the Mueller matrix of the BLASTPol HWP, equivalent to that shown in Fig. 15, but including in the fit the frequency-dependent position of the HWP equivalent axes (see Fig. 19).

achromatic design. We now postulate that most of the non-idealities we see in the measured HWP Mueller matrix (Fig. 15) are primarily due to the wavelength dependence of β_{ea} , along with the residual absorption from sapphire at $\sim 120 \text{ K}$. This hypothesis naturally ensues from the discussion presented in Section 2.1 on the scatter in frequency that results from any polarisation rotation on the PS sphere produced by a multiple-slab wave plate. The measurements of β_{ea} presented in Fig. 19 effectively quantify the area of the PS surface in which the various polarisation states regroup. One can imagine that the HWP performance would approach the ideal case once this effect is corrected for.

Therefore, we include $\beta_{\text{ea}}(\nu)$ in our Monte Carlo as a frequency-dependent offset in the array of rotation angles (so that $\theta \rightarrow \theta - \beta_{\text{ea}}$), and repeat our simulations. The results, presented in Fig. 20, can now be qualitatively compared to the Mueller matrix of an ideal HWP (Equation 3). The improvement is noticeable, especially in the off-diagonal elements, and the resemblance to an ideal HWP is remarkable across the entire spectral range of interest; this procedure effectively acts to diagonalise the HWP Mueller matrix. However, the transmission losses due to absorption from the sapphire at $\sim 120 \text{ K}$ still affect the diagonal elements of the matrix, as expected.

As a final improvement, we extrapolate the β_{ea} -corrected HWP Mueller matrix to 4 K by including in our Monte Carlo a correction for the residual sapphire absorption (using the data presented in Fig. 13). The results are shown in Fig. 21. Although there still seems to be residual

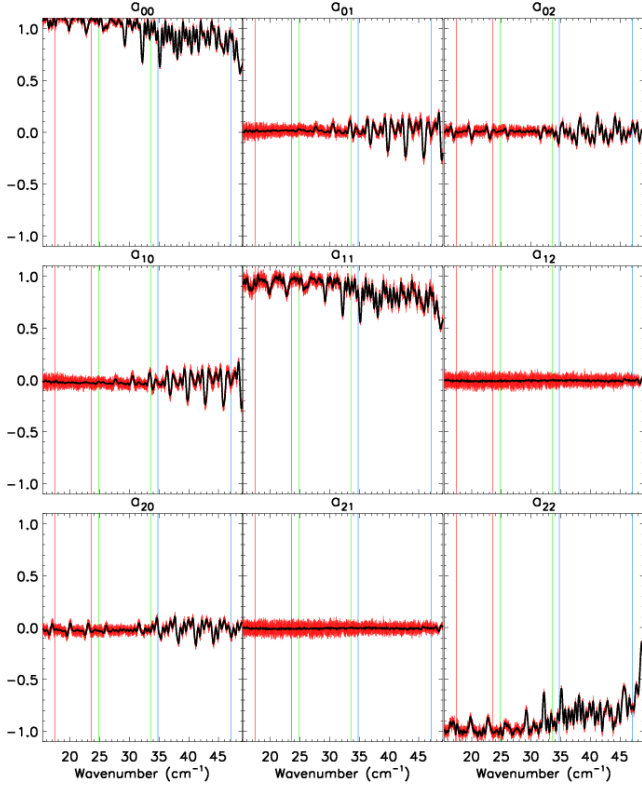


Figure 21. Graphical representation of the Mueller matrix of the BLASTPol HWP, equivalent to that shown in Fig. 20, but including a correction for the temperature dependence of the sapphire absorption coefficient (see Fig. 13).

transmission losses due to sapphire absorption at 250 and 350 μm , the retrieved HWP Mueller matrix is nearly that of an ideal HWP. The band-averaged values of the matrix coefficients for a flat-spectrum input source are reported in Table 2, along with their propagated uncertainty; the off-diagonal elements are always consistent with zero within 2σ and the modulus of the three diagonal coefficients is always >0.8 . The combination of these coefficients with the band-averaged values of β_{ea} given in Table 1 gives a complete account of the HWP non-idealities to the best of our ability.

We repeat the calculation of the band-averaged coefficients for the other spectral indices discussed in Fig. 19; we find values that are always within 1–2% of those reported in Table 2, and thus we do not explicitly report them here. Because the three diagonal elements of the HWP Mueller matrix effectively determine the HWP co-pol/cross-pol transmission and modulation efficiency, this analysis confirms that these quantities are very weakly dependent on the spectral index of the input source; these findings are in very good agreement with those of Savini et al. (2009). We will see in Section 5 how \bar{a}_{00} , \bar{a}_{11} , and \bar{a}_{22} can be incorporated in the map-making algorithm in terms of optical efficiency, η , and polarisation efficiency, ε , of each detector.

4.3 Effective HWP phase shift

Finally, we discuss a potential limitation to any linear polarisation modulator, i.e. the leakage between axes. In a HWP, the phase shift between the two axes should be as close to

| Band | 250 μm | 350 μm | 500 μm |
|----------------|--------------------|--------------------|--------------------|
| \bar{a}_{00} | 0.905 ± 0.006 | 1.001 ± 0.006 | 1.008 ± 0.007 |
| \bar{a}_{01} | 0.012 ± 0.010 | 0.017 ± 0.010 | 0.014 ± 0.011 |
| \bar{a}_{02} | -0.002 ± 0.008 | 0.006 ± 0.009 | 0.001 ± 0.009 |
| \bar{a}_{10} | -0.016 ± 0.010 | -0.021 ± 0.010 | -0.020 ± 0.011 |
| \bar{a}_{11} | 0.806 ± 0.011 | 0.928 ± 0.010 | 0.935 ± 0.012 |
| \bar{a}_{12} | -0.007 ± 0.011 | -0.009 ± 0.014 | -0.011 ± 0.014 |
| \bar{a}_{20} | -0.008 ± 0.008 | -0.022 ± 0.010 | -0.021 ± 0.010 |
| \bar{a}_{21} | -0.007 ± 0.011 | -0.009 ± 0.014 | -0.011 ± 0.014 |
| \bar{a}_{22} | -0.808 ± 0.008 | -0.960 ± 0.009 | -0.979 ± 0.010 |

Table 2. Band-averaged Mueller matrix coefficients. These values are relative to Fig. 21. The input source is assumed to have a flat spectrum in frequency.

180° as possible to avoid transforming linear polarisation into elliptical polarisation, hence losing efficiency. The phase can not be directly measured in a pFTS, but it can be indirectly inferred from the HWP Mueller matrix.

In order to recover the wavelength-dependent phase shift of the HWP, we recall the Mueller matrix of a non-ideal impedance-matched single birefringent slab (Savini et al. 2009, at $\theta = 0^\circ$):

$$\mathcal{M}_{\text{slab}}(\theta = 0^\circ, \Delta\varphi) = \frac{1}{2} \times \quad (14)$$

$$\times \begin{pmatrix} \alpha^2 + \beta^2 & \alpha^2 - \beta^2 & 0 & 0 \\ \alpha^2 - \beta^2 & \alpha^2 + \beta^2 & 0 & 0 \\ 0 & 0 & 2\alpha\beta\cos\Delta\varphi & 2\alpha\beta\sin\Delta\varphi \\ 0 & 0 & -2\alpha\beta\sin\Delta\varphi & 2\alpha\beta\cos\Delta\varphi \end{pmatrix}.$$

By comparing the matrix in Equation 14 with that of a generic HWP, we can solve for the HWP phase shift as

$$\cos\Delta\varphi = \frac{a_{22}}{2} \left(\frac{a_{00} + a_{01}}{2} \right)^{-\frac{1}{2}} \left(\frac{a_{00} - a_{01}}{2} \right)^{-\frac{1}{2}}. \quad (15)$$

Equation 15 allows us to recover the phase shift from our knowledge of a_{00} , a_{01} and a_{22} . Fig. 22 shows the estimated phase shift of the BLASTPol HWP as a function of wavenumber, before and after the introduction in our Monte Carlo routine of the wavelength-dependent position of the HWP equivalent axes depicted in Fig. 19. The improvement is striking, and confirms the fact that most of the HWP non-idealities due to the achromatic design can be more easily modelled by estimating $\beta_{\text{ea}}(\nu)$. This finding further encourages us to implement β_{ea} in the map-making code.

Nonetheless, the β_{ea} -corrected phase shift appreciably departs from 180° . We have anticipated that this discrepancy is primarily due to the ~ 0.047 mm difference between the desired thickness of the single sapphire substrates and what was available on the market; at 350 μm , this translates to a deviation of $\sim 15^\circ$ from ideality, which accounts for roughly 60–75% of the measured non-ideality. The remaining 25–40% can be qualitatively explained by recalling that Equation 15 strictly applies only to a single birefringent plate. In a multi-slab Pancharatnam stack, $\Delta\varphi$ becomes an “effective” phase shift as we are no longer in the presence of a pure cosine modulation, thus slightly skewing the HWP modulation function and resulting in an artificially higher leakage between axes when the cosine function is inverted.

However, we have indications that the modulation efficiency of the HWP at 4 K is only mildly affected by this

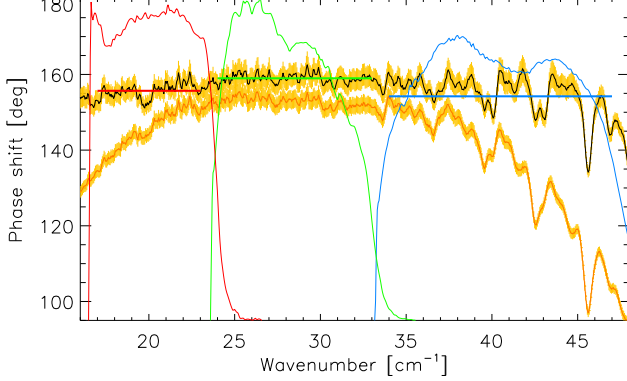


Figure 22. HWP phase shift as a function of wavenumber, before (orange) and after (black) implementing in the Monte Carlo the wavelength-dependent position of the HWP equivalent axes (Fig. 19). The (3σ) error bars (in yellow) are obtained by propagating the error on the Mueller matrix coefficients. The band-averaged values of the phase shift (for a flat-spectrum input source) are drawn as thick horizontal lines (only for the upper black line). Also shown for reference is the relative spectral response of the three BLASTPol channels, in arbitrary units.

departure from ideality. From Fig. 14b we see that the extrapolated HWP modulation efficiency is always above 95% across the whole spectral range of interest, with band-integrated values exceeding 98%. Moreover, phase shift deviations of similar amplitude are measured in most mm and submm-wave achromatic half-wave plates manufactured to date (e.g., Savini et al. 2009; Zhang et al. 2011)

Incidentally, we verify that our methodology does not violate conservation of energy by ensuring that the output Stokes vector resulting from a generic polarised input travelling through the recovered HWP Mueller matrix satisfies $I^2 \geq Q^2 + U^2$ in every instance describe above.

5 MAP-MAKING ALGORITHM

Map-making is the operation that generates an astronomical map, which contains in every pixel an estimate of the sky emission, and is obtained by combining data from all detectors available at a given wavelength channel, their noise properties and the pointing information. The raw data consist of bolometer time-ordered streams (or timelines), which are cleaned and pre-processed before being fed into the map-maker: in order, cosmic rays are flagged and removed, the known electronics transfer function is deconvolved from the data streams, an elevation-dependent common-mode signal due to the residual atmosphere is removed concurrently with a polynomial fit to the data, and finally the timelines are high-pass filtered to suppress the low-frequency ($1/f$) noise. The details of the pre-processing of the BLAST timelines are extensively described elsewhere (Rex 2007; Truch 2007; Wiebe 2008; Pascale et al. 2008), and we refer to these works for a complete account of the low-level data reduction. The process of cleaning and preparing the bolometer time-streams for map-making in BLASTPol has closely followed that of BLAST, except for the removal of discontinuities in the DC level of the bolometer, caused by the HWP being stepped approximately every 15 minutes (this operation is

performed before the high-pass filtering); also, the subtraction of an elevation-dependent term from the timelines was not needed in BLAST.

In the following, we focus on the mathematical formalism of the map-making technique, and its algorithmic implementation in the specific case of BLASTPol.

5.1 Maximum likelihood map-making

For a non-ideal polarisation experiment, by adopting the Stokes formalism and assuming that no circular (V) polarisation is present, we can model the data as

$$d_t^i = \frac{\eta^i}{2} A_{tp}^i \left[I_p + \varepsilon^i \left(Q_p \cos 2\gamma_t^i + U_p \sin 2\gamma_t^i \right) \right] + n_t^i. \quad (16)$$

Here: i , t and p label detector index, time, and map pixel respectively; d_t^i are the time-ordered data for a given channel, related to the sky maps $[I_p, Q_p, U_p]$ by the pointing operator A_{tp}^i ; η^i is the optical efficiency of each detector; ε^i is the polarisation efficiency of each detector with its polarising grid (analyser); and n_t^i represents a generic time-dependent noise term. Throughout this discussion it is assumed that the term within square brackets is the convolution of the sky emission with the telescope point-spread function (PSF). γ_t^i is the time-ordered vector of the observed polarisation angle, defined as the angle between the polarisation reference vector at the sky pixel p (in the chosen celestial frame) and the polarimeter transmission axis. γ_t^i is given by

$$\gamma_t^i = \alpha_t^i + 2 [\beta_t - \beta_0 - \bar{\beta}_{\text{ea}}] + \delta_{\text{grid}}^i, \quad (17)$$

where α_t^i is the angle between the reference vector at pixel p and a vector pointing from p to the zenith along a great circle, β_t is the HWP orientation angle in the instrument frame, β_0 is the HWP zero angle in the instrument frame, $\bar{\beta}_{\text{ea}}$ is the band-averaged position of the equivalent axes of the HWP (dependent on the known or assumed spectral signature of the input source; see Section 4.2), and $\delta_{\text{grid}}^i = [0, \pi/2]$ accounts for the transmission axis of the polarising grids being parallel/perpendicular to the zenith angle.

The notation outlined above can be connected to the Mueller formalism developed in Section 4.1 to determine under which circumstances Equation 16 is valid in the presence of a real (i.e., non-ideal) HWP. Because we have included in Equation 17 the band-averaged position of the equivalent axes of the HWP, $\bar{\beta}_{\text{ea}}$, the Mueller matrix of the BLASTPol HWP can be considered almost that of an ideal HWP, as discussed in Section 4.2. Nonetheless, we have shown that the band-averaged values of the three diagonal matrix coefficients are not identically unity (but always > 0.8 in modulus), probably as a result of residual absorption from sapphire, especially in the 250 and 350 μm bands (although we have corrected for it to the best of our knowledge).

In the light of these considerations, we now want to compare Equation 16 to Equation 8, which both represent the signal measured by a polarisation insensitive intensity detector when illuminated by a polarised input that propagates through a rotating HWP and an analyser. A term-by-term comparison shows that these two expressions are equivalent when the coefficients B and C (defined in Equation 9) are zero, i.e. when the HWP modulates the polarisation purely at four times the rotation angle, with no leakage in the second harmonic (twice the rotation angle) and thus no leakage

of I into Q and U . These two coefficients are linear combinations of the HWP Mueller matrix elements $\bar{a}_{01}, \bar{a}_{10}, \bar{a}_{02}, \bar{a}_{20}$, which we have shown in Table 2 to be all compatible with zero within 2σ . In addition, their amplitude is at most $\sim 2\%$ of that of the diagonal matrix elements, and in the limit of elevated polarisation angle coverage, $\langle \cos 2\gamma \rangle^2 + \langle \sin 2\gamma \rangle^2 \approx 0$, these terms (in twice the rotation angle) effectively average out in the sums. Therefore, the coefficients B and C can be neglected to first order, and the two expressions can be considered equivalent. Nonetheless, these generally moderate levels of $I \rightarrow Q, U$ leakage can be readily accounted for by incorporating in the map-making algorithm a correction for the “instrumental polarisation” (IP).

In addition, after some elementary algebra, it can be shown that $\eta = a_{00} + \frac{a_{11}}{2} + \frac{a_{22}}{2}$ and $\eta\varepsilon = \frac{a_{11}}{2} - \frac{a_{22}}{2}$. As anticipated in Section 4.2, the knowledge of the band-averaged values of the three diagonal matrix elements, $\bar{a}_{00}, \bar{a}_{11}, \bar{a}_{22}$ (which we have shown to depend weakly on the spectral index of the input source), can be readily incorporated in the map-making algorithm in terms of optical efficiency, η , and polarisation efficiency, ε , of the HWP; these can be factored into the overall optical efficiency and polarisation efficiency of each detector. From the values listed in Table 2, in our case we find $[\eta_{\text{hwp}}, \varepsilon_{\text{hwp}}] = [0.904, 0.893], [0.985, 0.958]$, and $[0.986, 0.971]$ at 250, 350, and 500 μm , respectively.

Finally, the comparison of Equations 16 and Equation 8 also yields $\eta\varepsilon\chi = -a_{12} = -a_{21}$, where we have introduced a new parameter, χ , which quantifies the amplitude of the mixing of Q and U . From Table 2, we see that $\bar{a}_{12} = \bar{a}_{21}$ are always compatible with zero within 1σ , and their amplitude is at most $\sim 1\%$ of that of the diagonal matrix elements. Nonetheless we quantify the amplitude of the $Q \leftrightarrow U$ mixing to be $\chi_{\text{hwp}} = 0.009, 0.010$, and 0.011 at 250, 350, and 500 μm , respectively. While this correction is not currently included in our algorithm, we indicate that it can be implemented in a relatively straightforward way by modifying Equation 16 with a double change of variable, i.e. $Q \rightarrow Q + \chi U$ and $U \rightarrow U + \chi Q$. If χ is estimated to the required accuracy, the unmixed Q and U can be retrieved unbiasedly. This correction may be very relevant to CMB polarisation experiments, where any $Q \leftrightarrow U$ leakage leads to a spurious mixing of the EE and BB modes.

We remind the reader that the above factors have been computed directly from the band-averaged coefficients of the inferred HWP Mueller matrix extrapolated to 4 K, and offer a direct way to include the modelled HWP non-idealities in a map-making algorithm. On the other hand, the band-averaged HWP maximum transmission, polarisation efficiency and cross-pol quoted at the end of Section 3.3 are estimated directly from the spectra extrapolated to 4 K, and are mostly informative from an experimental point of view rather than for data analysis purposes.

Consider now one map pixel p that is observed in one band by k detectors ($i = 1, \dots, k$); let us define the generalised pointing matrix \mathbf{A}_{tp} , which includes the trigonometric

functions along with the efficiencies,

$$\mathbf{A}_{tp} \equiv \frac{1}{2} \begin{pmatrix} \eta^1 A_{tp}^1 & \eta^1 \varepsilon^1 A_{tp}^1 \cos 2\gamma_t^1 & \eta^1 \varepsilon^1 A_{tp}^1 \sin 2\gamma_t^1 \\ \vdots & \vdots & \vdots \\ \eta^i A_{tp}^i & \eta^i \varepsilon^i A_{tp}^i \cos 2\gamma_t^i & \eta^i \varepsilon^i A_{tp}^i \sin 2\gamma_t^i \\ \vdots & \vdots & \vdots \\ \eta^k A_{tp}^k & \eta^k \varepsilon^k A_{tp}^k \cos 2\gamma_t^k & \eta^k \varepsilon^k A_{tp}^k \sin 2\gamma_t^k \end{pmatrix}, \quad (18)$$

and the map triplet \mathbf{S}_p , along with the combined detector (\mathcal{D}_t) and noise (\mathbf{n}_t) timelines,

$$\mathbf{S}_p \equiv \begin{pmatrix} I_p \\ Q_p \\ U_p \end{pmatrix}, \quad \mathcal{D}_t \equiv \begin{pmatrix} d_t^1 \\ \vdots \\ d_t^i \\ \vdots \\ d_t^k \end{pmatrix}, \quad \mathbf{n}_t \equiv \begin{pmatrix} n_t^1 \\ \vdots \\ n_t^i \\ \vdots \\ n_t^k \end{pmatrix}. \quad (19)$$

Equation 16 can then be rewritten in compact form as

$$\mathcal{D}_t = \mathbf{A}_{tp} \mathbf{S}_p + \mathbf{n}_t. \quad (20)$$

Under the assumption that the noise is Gaussian and stationary, the likelihood of \mathbf{S}_p given the data can be maximised, thus yielding the well-known generalised least squares (GLS) estimator for \mathbf{S}_p :

$$\tilde{\mathbf{S}}_p = \left(\mathbf{A}_{tp}^T \mathbf{N}^{-1} \mathbf{A}_{tp} \right)^{-1} \mathbf{A}_{tp}^T \mathbf{N}^{-1} \mathcal{D}_t, \quad (21)$$

where \mathbf{N} is the noise covariance matrix of the data in the time domain,

$$\mathbf{N} \equiv \langle \mathbf{n}_t \mathbf{n}_{t'}^T \rangle = \begin{pmatrix} \langle n_t^1 n_{t'}^1 \rangle & \cdots & \langle n_t^1 n_{t'}^i \rangle & \cdots & \langle n_t^1 n_{t'}^k \rangle \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \langle n_t^i n_{t'}^1 \rangle & \cdots & \langle n_t^i n_{t'}^i \rangle & \cdots & \langle n_t^i n_{t'}^k \rangle \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \langle n_t^k n_{t'}^1 \rangle & \cdots & \langle n_t^k n_{t'}^i \rangle & \cdots & \langle n_t^k n_{t'}^k \rangle \end{pmatrix}, \quad (22)$$

with t, t' running over the detector time samples (typically $N_s \sim 10^6 - 10^7$).

Computation of the solution to Equation 21 is far from trivial in most astronomical applications, due to \mathbf{N} being a very large matrix, of size $kN_s \times kN_s$. Understandably, it is computationally challenging to invert this matrix, especially when there are correlations among detectors, and a number of “optimal” map-making techniques have been developed in the literature to tackle this problem (e.g., Natoli et al. 2001, 2009; Masi et al. 2006; Johnson et al. 2007; Wu et al. 2007; Patanchon et al. 2008; Cantalupo et al. 2010).

5.2 Naive binning

In the simple case that the noise is uncorrelated between different detectors, the matrix in Equation (22) reduces to block diagonal:

$$\langle n_t^i n_{t'}^j \rangle = \langle n_t^j n_{t'}^i \rangle = 0 \quad (i \neq j). \quad (23)$$

In addition, let us assume that there is no correlation between noise of different samples acquired by the same detector, or, in other words, that the noise in each detector is white. From Equations (22) and (23), we can see that each “block” of the noise covariance matrix collapses into

one value, which is the timeline variance for each detector. Hence, \mathbf{N} becomes a $k \times k$ diagonal matrix where the diagonal elements are the sample variances of the detectors, σ_i^2 , and weights can thus be defined as the inverse of those variances, $w^i \equiv 1/\sigma_i^2$.

Therefore, under the assumption that the noise is white and uncorrelated among detectors, Equation (21) reduces to a simple, weighted binning (“naive” binning; see also Pascale et al. 2011) of the map:

$$\mathbf{S}_p = \begin{pmatrix} I_p \\ Q_p \\ U_p \end{pmatrix} = \frac{\sum_{i=1}^k \sum_{t=1}^{N_s} w^i \frac{(\mathbf{A}_{tp}^i)^T d_t^i}{(\mathbf{A}_{tp}^i)^T \mathbf{A}_{tp}^i}}{\sum_{i=1}^k w^i}. \quad (24)$$

In the light of these considerations, let us go back to Equation (16) and model the generic time-dependent noise term n_t^i as

$$n_t^i = u_t + \xi^i \rho_t, \quad (25)$$

where u_t represents a time-dependent noise term, completely uncorrelated among different detectors, while ρ_t describes the correlated noise (varying over timescales larger than the ratio of the size of the detector array to the scan speed), coupled to each detector via the ξ^i parameter, peculiar to each bolometer.

Let us define the following quantity for every pixel p in the map:

$$\mathbf{S}_p^e = \begin{pmatrix} I_p^e \\ Q_p^e \\ U_p^e \end{pmatrix} \equiv \begin{pmatrix} \sum_{i=1}^k \sum_{t=1}^{N_s} d_t^i \\ \sum_{i=1}^k \sum_{t=1}^{N_s} d_t^i \cos 2\gamma_t^i \\ \sum_{i=1}^k \sum_{t=1}^{N_s} d_t^i \sin 2\gamma_t^i \end{pmatrix}, \quad (26)$$

where N_s is now the number of samples in each detector timeline that fall within pixel p , and the superscript “e” stands for “estimated”. The above quantities can be computed directly from the detector timelines. Recalling Equations (16) and (25), we can outline the following linear system of 3 equations with 3 unknowns:

$$\begin{pmatrix} I_p^e \\ Q_p^e \\ U_p^e \end{pmatrix} = \begin{pmatrix} \sum_{i,t} 1 & \sum_{i,t} \cos 2\gamma_t^i & \sum_{i,t} \sin 2\gamma_t^i \\ \sum_{i,t} \cos 2\gamma_t^i & \sum_{i,t} \cos^2 2\gamma_t^i & \sum_{i,t} \cos 2\gamma_t^i \sin 2\gamma_t^i \\ \sum_{i,t} \sin 2\gamma_t^i & \sum_{i,t} \cos 2\gamma_t^i \sin 2\gamma_t^i & \sum_{i,t} \sin^2 2\gamma_t^i \end{pmatrix} \cdot \frac{1}{2} \begin{pmatrix} I_p \\ Q_p \\ U_p \end{pmatrix} + \begin{pmatrix} \sum_{i,t} (u_t + \xi^i \rho_t) \\ \sum_{i,t} (u_t + \xi^i \rho_t) \cos 2\gamma_t^i \\ \sum_{i,t} (u_t + \xi^i \rho_t) \sin 2\gamma_t^i \end{pmatrix},$$

where we have temporarily assumed $\eta^i = \varepsilon^i = w^i = 1$ and combined the two sums in one, with the indices i and t running, respectively, over the bolometers and the samples in each detector timeline.

If we now define the quantities,

$$\begin{aligned} N_{\text{hit}} &\equiv \sum_{i,t} \frac{1}{2}, & c &\equiv \sum_{i,t} \frac{1}{2} \cos 2\gamma_t^i, \\ c_2 &\equiv \sum_{i,t} \frac{1}{2} \cos^2 2\gamma_t^i, & s &\equiv \sum_{i,t} \frac{1}{2} \sin 2\gamma_t^i, \\ s_2 &\equiv \sum_{i,t} \frac{1}{2} \sin^2 2\gamma_t^i = N_{\text{hit}} - c_2, & U &\equiv \sum_{i,t} u_t, \\ m &\equiv \sum_{i,t} \frac{1}{2} \cos 2\gamma_t^i \sin 2\gamma_t^i, & C_2^u &\equiv \sum_{i,t} u_t \cos 2\gamma_t^i \\ S_2^u &\equiv \sum_{i,t} u_t \sin 2\gamma_t^i, & P &\equiv \sum_{i,t} \xi^i \rho_t, \\ C_2^\rho &\equiv \sum_{i,t} \xi^i \rho_t \cos 2\gamma_t^i, & S_2^\rho &\equiv \sum_{i,t} \xi^i \rho_t \sin 2\gamma_t^i, \end{aligned} \quad (27)$$

then the system in Equation (27) can be rewritten in compact form as

$$\begin{pmatrix} I_p^e \\ Q_p^e \\ U_p^e \end{pmatrix} = \begin{pmatrix} N_{\text{hit}} & c & s \\ c & c_2 & m \\ s & m & N_{\text{hit}} - c_2 \end{pmatrix} \cdot \begin{pmatrix} I_p \\ Q_p \\ U_p \end{pmatrix} - \begin{pmatrix} U + P \\ C_2^u + C_2^\rho \\ S_2^u + S_2^\rho \end{pmatrix}. \quad (28)$$

In order to retrieve an estimate of \mathbf{S}_p from the quantities computed in Equation (26), the above system has to be solved for every pixel p in the map. One can already see the computational advantage of inverting a 3×3 matrix $N_{\text{pix}} \times N_{\text{pix}}$ times, with respect to the inversion of a generic $kN_s \times kN_s$ matrix (for detectors having uncorrelated $1/f$ noise as well as a common-mode $1/f$ noise; Patanchon et al. 2008), or k matrices of size $N_s \times N_s$ (for detectors having only uncorrelated $1/f$ noise; Cantalupo et al. 2010). The main difficulties are, of course, in estimating the noise terms $U, P, C_2^u, C_2^\rho, S_2^u, S_2^\rho$. However, recalling Equation (17) and the fact that adjacent detectors have orthogonal polarising grids ($\delta_{\text{grid}}^i = [0, \pi/2]$), we note that, in the sum over i , adjacent detectors have equal and opposite contributions to C_2^ρ and S_2^ρ , under the following assumptions: (i) the timescale over which the correlated noise is approximately constant is larger than the time elapsed while scanning the same patch of sky with two adjacent detectors, and (ii) ξ^i is not too dissimilar between adjacent bolometers.

This means that the terms C_2^ρ and S_2^ρ can be neglected, under the above assumptions, while estimating the $[Q, U]$ maps. In particular, as a first step, we can solve for I only by high-pass filtering the timelines, in order to suppress the correlated noise term in I, P . Subsequently, I can be assumed known, and the $[Q, U]$ maps can be computed without filtering the timelines, so that polarised signal at large angular scales is not suppressed. In fact, we see from Equation (16) that in the limit of elevated angle coverage, the term in I , not being modulated at four times the HWP rotation angle, effectively averages out in the sums.

The other assumption required for the naive binning is that the noise is white, at least on the timescales relevant to BLASTPol’s scan strategy. An analysis of the bolometer timelines from the 2010 campaign shows that the knee of the $1/f$ noise in the difference between two adjacent detectors is typically located at frequencies $\lesssim 0.1$ Hz; assuming a typical scan speed of 0.1° s^{-1} , this corresponds to angular scales of $\gtrsim 1^\circ$ on the sky. The regions mapped by BLASTPol hardly exceed 1° in size (see Table 1.1 in Moncelsi 2011), hence here

we stipulate that the noise in the difference between pairs of adjacent detectors is white.

Therefore, under the assumptions above, we can solve the linear system outlined in Equation (28); by defining the following quantities,

$$\begin{aligned} \Delta &\equiv c^2 (c_2 - N_h) - N_h (c_2^2 + m^2 - c_2 N_h) + 2 c s m - c_2 s^2, \\ A &\equiv -(c_2^2 + m^2 - c_2 N_h), \quad B \equiv c (c_2 - N_h) + s m, \\ C &\equiv c m - s c_2, \quad D \equiv -(c_2 - N_h) N_h + s^2, \\ E &\equiv c s - m N_h, \quad F \equiv c_2 N_h - c^2, \end{aligned} \quad (29)$$

the solution to the system can be written in compact form:

$$\mathbf{S}_p = \begin{pmatrix} I_p \\ Q_p \\ U_p \end{pmatrix} = \begin{pmatrix} \frac{A I_p^e + B Q_p^e + C U_p^e}{\Delta} \\ \frac{B I_p^e + D Q_p^e + E U_p^e}{\Delta} \\ \frac{C I_p^e + E Q_p^e + F U_p^e}{\Delta} \end{pmatrix}, \quad (30)$$

where we have renamed $N_{\text{hit}} \rightarrow N_h$ for brevity.

5.3 Weights and uncertainties

The solution for \mathbf{S}_p given in Equation (30) is a simple, unweighted binning of the data into the map pixels. In reality, as anticipated in Equation (24), we want to perform a weighted binning, where the weight of each detector is given by the inverse of its timeline variance, which can be easily measured as the bolometer's white noise floor level. In our formalism, the weighted binning is simply achieved by defining $[I_p^e, Q_p^e, U_p^e]$ in Equation (26), as well as each of the quantities N_h , c , s , c_2 , s_2 , and m introduced in Equation (27), to include w^i in the sums. Similarly, the measured values of the optical efficiencies η^i and polarisation efficiencies ε^i can readily be inserted in Equation (27) to account for the non-idealities of the optical system.

The introduction of the weights allows us to derive the expression for the statistical error on \mathbf{S}_p , in the continued assumption of uncorrelated noise, following the usual error propagation formula (e.g., Press et al. 1992, here we omit the sum over t for simplicity):

$$\sigma_p^2 = \sum_i \frac{1}{w^i} \left(\frac{\partial \mathbf{S}_p}{\partial d^i} \right)^2. \quad (31)$$

After some tedious algebra, the expression for the statistical error is

$$\sigma_p^2 = \begin{pmatrix} \text{Var}_p^I \\ \text{Var}_p^Q \\ \text{Var}_p^U \end{pmatrix} = \begin{pmatrix} \frac{2}{\Delta^2} (A^2 N_h + B^2 c_2 + C^2 s_2 + 2 A B c + 2 A C s + 2 B C m) \\ \frac{2}{\Delta^2} (B^2 N_h + D^2 c_2 + E^2 s_2 + 2 B D c + 2 B E s + 2 D E m) \\ \frac{2}{\Delta^2} (C^2 N_h + E^2 c_2 + F^2 s_2 + 2 C E c + 2 C F s + 2 E F m) \end{pmatrix},$$

where $s_2 \equiv N_h - c_2$, as noted in Equation (27). To first order, these expressions can be used to quantify the uncertainty of $[I, Q, U]$ in each map pixel p . A more comprehensive account of the correlations in the noise, as well as a thorough validation of the assumptions made here, is beyond the scope of this paper and will be treated in a future work.

5.4 Preliminary map

As a proof of concept of the naive binning technique for the BLASTPol polarised map-maker, which includes all the cor-

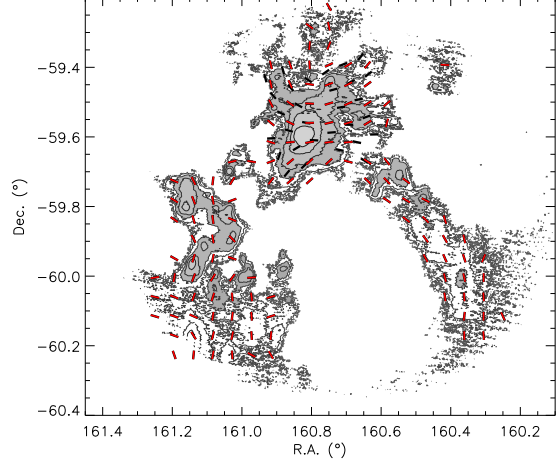


Figure 23. Preliminary BLASTPol map at $500 \mu\text{m}$ of the Carina Nebula, a giant molecular cloud approximately centred at coordinates $[10^{\text{h}}42^{\text{m}}35^{\text{s}}, -59^{\circ}42'15'']$. The intensity contour levels are shown in the background. The pseudo-vectors indicate the inferred magnetic field direction: the BLASTPol measurements (red) are in excellent agreement with those from the SPARO polarimeter at $450 \mu\text{m}$ (black; Li et al. 2006). This map should not be considered of any scientific value as no absolute calibration has been applied to the intensity contours; the map is only shown as a proof of concept for the map-maker, which includes all the corrections due to HWP non-idealities discussed in this work. Here we adopt $\bar{\beta}_{\text{ea}}^{500 \mu\text{m}} = 1.7$, calculated assuming a spectral index for the dust emissivity of 1.37 (Salatino et al. 2012).

rections due to HWP non-idealities discussed in this work, we present a *preliminary* map at $500 \mu\text{m}$ of one of the giant molecular clouds observed by BLASTPol, the Carina Nebula. In this specific case, we calculate $\bar{\beta}_{\text{ea}}^{500 \mu\text{m}} = 1.7$ based on a dust emissivity spectral index of 1.37 (Salatino et al. 2012) for a modified blackbody spectral energy distribution.

The map in Fig. 23 is presented as contour levels of the intensity map I , upon which we superimpose pseudo-vectors indicating the inferred magnetic field direction on the sky (assumed to be perpendicular to the measured polarisation direction; see Lazarian 2007). The sky polarisation angle is given by $\phi = \frac{1}{2} \arctan \frac{U}{Q}$. Because the absolute flux calibration has not been finalised yet, we choose not to report here the intensity values corresponding to each contour level. This map should not be considered of any scientific value as it is not calibrated in flux. Nonetheless, we find a remarkable agreement between the BLASTPol polarisation directions at $500 \mu\text{m}$ and those produced by the Submillimeter Polarimeter for Antarctic Remote Observations (SPARO; Novak et al. 2003) at $450 \mu\text{m}$, which are shown in Fig. 1 of Li et al. (2006) and whose pseudo-vectors are reported in Fig. 23 for comparison. Here the original BLASTPol $[I, Q, U]$ maps have been smoothed with a kernel of $4'$ (FWHM) for a more direct comparison with the SPARO data.

6 CONCLUDING REMARKS

The goal of the first part of this work was to identify and measure the parameters that fully characterise the spectral performance of the linear polarisation modulator integrated

in the BLASTPol instrument, a cryogenic achromatic half-wave plate.

We have described in detail the design and manufacturing process of a five-slab sapphire HWP, which is, to our knowledge, the most achromatic built to date at submm wavelengths. In the same context, we have provided a useful collection of spectral data from the literature for the sapphire absorption coefficient at cryogenic temperatures.

Using a polarising FTS, we have fully characterised the spectral response of the anti-reflection coated BLASTPol HWP at room temperature and, unprecedentedly, at 120 K; we have acquired data cubes by measuring spectra while rotating the HWP to produce the polarisation modulation.

The cold dataset contains measurements in both co-pol and cross-pol configurations; we have used these two data cubes to estimate 9 out of 16 elements of the HWP Mueller matrix as a function of frequency. We have developed an ad-hoc Monte Carlo algorithm that returns for every frequency the best estimate of each matrix element and the associated error, which is a combination of the uncertainty on the measured spectra and a random jitter on the rotation angle.

We have measured how the position of the equivalent axes of the HWP, β_{ea} , changes as a function of frequency, an effect that is inherent to any achromatic design. Once this dependence is accounted for in the Monte Carlo, and a correction is implemented for the residual absorption from sapphire, the Mueller matrix of the HWP approaches that of an ideal HWP, at all wavelengths of interest. In particular, the (band-averaged) off-diagonal elements are always consistent with zero within 2σ and the modulus of the three diagonal coefficients is always > 0.8 . Therefore, we have introduced in the BLASTPol map-making algorithm the band-integrated values of β_{ea} as an additional parameter in the evaluation of the polarisation angle. To first order, this approach allows us to account for most of the non-idealities in the HWP.

We have investigated the impact of input sources with different spectral signatures on β_{ea} and on the HWP Mueller matrix coefficients. We find that the HWP transmission and modulation efficiency are very weakly dependent on the spectral index of the input source, whereas the position of the equivalent axes of the sapphire plate stack is more significantly affected. This latter dependence, if neglected, may lead to an arbitrary rotation of the retrieved polarisation angle on the sky of magnitude $2\bar{\beta}_{\text{ea}} = 10\text{--}15^\circ$ ($3\text{--}5^\circ$) at 250 (500) μm . The 350 μm band, however, is minimally perturbed by this effect.

In principle, the measured Mueller matrix can be used to generate a synthetic time-ordered template of the polarisation modulation produced by the HWP as if it were continuously rotated at a mechanical frequency $f = \omega t$. Continuous rotation of the HWP allows the rejection of all the noise components modulated at harmonics different than $4f$ (synchronous demodulation) and is typically employed by experiments optimised to measure the polarisation of the CMB (e.g., Johnson et al. 2007; Reichborn-Kjennerud et al. 2010). In such experiments, the HWP modulation curve leaves a definite synchronous imprint on the time-ordered bolometer data streams (timelines), hence it is of utter importance to characterise the template and remove it from the raw data. However, a time-ordered HWP template would be of no use to a step-and-integrate experiment such as BLAST-

Pol, whose timelines are not dominated by the HWP synchronous signal.

We have measured the phase shift of the HWP across the wavelength range of interest to be $\sim 160^\circ$, which appreciably deviates from the ideal 180° ; this is primarily due to the unavailability on the market of sapphire substrates with the exact desired thickness. However, the modulation efficiency of the HWP is only mildly affected by this departure from ideality, being above 98% in all three BLASTPol bands. Moreover, departures of similar amplitude are not uncommon for HWPs at mm and submm wavelengths.

The goal of the second part of this work was to include the measured non-idealities of the HWP as-built in a map-making algorithm. We have focused on the implementation of a naive binning technique for the case of BLASTPol, under the assumption of white and uncorrelated noise. As a proof of concept, we have presented a preliminary polarisation map for one of the scientific targets observed by BLASTPol during its first Antarctic flight, completed in January 2011. The inferred direction for the local magnetic field in the Carina Nebula star-forming region is in excellent agreement with the results obtained by Li et al. (2006) with the SPARO instrument. The empirical approach presented in this paper will ultimately yield unprecedented accuracy on astronomical measurements of the polarisation angle on the sky at submm wavelengths.

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